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Malleable Interactive surfaces for distant mobile tangible interaction

Juan Rosso

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THÈSE

Pour obtenir le grade de

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Présentée par

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préparée au sein du **Laboratoire d'Informatique de Grenoble**
dans l'**École Doctorale Mathématiques, Sciences et
Technologies de l'Information, Informatique**

Surfaces Malléables pour l'Interaction Mobile et Tangible a Distance

Malleable Interactive Surfaces for Distant Mobile Tangible Interaction

Thèse soutenue publiquement le **14 Décembre 2018**,
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Abstract

Sliders are one of the most used widgets on mobile devices for the adjustment of continuous parameters such as screen brightness or speaker sound volume. On mobile devices, sliders are represented graphically, and thus require the user's visual attention to operate them. This visual dependency can be a problem for professionals, such as audio or light engineers and data scientists, that require eyes-free interaction while adjusting continuous parameters. Furthermore, sliders are usually long and positioned in a vertical or horizontal way. As a consequence, when mobile devices are operated in a one-handed manner, the thumb cannot reach all the areas of the slider. In this thesis, we focus on new eyes-free one-handed interaction techniques to efficiently operate sliders on mobile devices.

To inform the design of new interaction techniques, we establish a design space inspired on our review of existing techniques for eyes-free interaction and one-handed interaction. We then validate the ability of the design space to guide the design of new interaction techniques, through the design of three new interaction techniques. The designed interaction techniques were also inspired on an existing concept for eyes-free interaction, which envisions shape-changing mobile devices capable of protruding tangible controls out of the display surface.

The techniques rely on shape-changing tangible sliders capable of changing different design properties such as orientation, length and side of the device where it is presented. For our first design, we analyze the impact that the orientation and length of a tangible slider has on performance when operated with a single hand. For our second design, we analyze the performance of an extendable tangible slider that allows clutching to keep operation within the comfortable area of the thumb. For our third design, we analyze the performance of a dual-side tangible slider that allows operation within the comfortable area of the thumb, and beyond this area, with the index finger on the back of the device.

Based on the results of seven different experiments, we then suggest that:

1. a conventional tangible slider delivers good performance but requires handgrip changes when acquiring targets in a distance of 70mm.
2. a dual-side tangible slider delivers good performance and supports a stable handgrip when acquiring targets in a distance of 100mm.
3. an extendable tangible slider delivers good performance and supports a stable handgrip when acquiring targets in a distance of 200mm.

Moreover, the performed experiments allow us to explore an area of shape-changing tangible user interfaces that has barely been studied: manipulation during shape-change. Our studies show how different shape-changing design characteristics, like the orientation and amplitude, can impact the interaction.

Résumé

Les curseurs linéaires sont l'un des widgets les plus utilisés sur les dispositifs mobiles pour l'ajustement des paramètres continus comme la luminosité de l'écran ou le volume sonore du haut-parleur. Sur les dispositifs mobiles, les curseurs sont représentés graphiquement, et en conséquence, ils nécessitent l'attention visuelle de l'utilisateur pour être opérés. Cette dépendance visuelle peut être un problème pour les professionnels, comme les ingénieurs du son ou les éclairagistes, qui ont besoin d'ajuster des paramètres sans regarder l'écran. De plus, les curseurs sont généralement longs et positionnés verticalement ou horizontalement. Par conséquent, quand les dispositifs mobiles sont opérés à une seule main, le pouce ne peut pas atteindre toute la longueur du curseur. Dans cette thèse, nous nous concentrons sur de nouvelles techniques d'interaction à une main sans regarder l'écran pour opérer efficacement les curseurs sur les dispositifs mobiles.

Pour informer la conception de nouvelles techniques d'interaction, nous établissons d'abord un espace de conception inspiré par notre examen des techniques existantes visant l'interaction sans regarder l'écran et à une main. Nous validons ensuite sa capacité à guider la conception de nouvelles techniques d'interaction, via son utilisation pour la conception de trois nouvelles techniques d'interaction. Ces nouvelles techniques d'interaction s'inspirent également d'un concept existant qui propose des dispositifs mobiles capables de faire ressortir des contrôles tangibles émergeant de la surface d'affichage.

Les techniques conçues reposent sur des curseurs tangibles qui changent de forme, capables de modifier différentes propriétés de conception comme l'orientation, la longueur et le côté du dispositif mobile sur lequel ils apparaissent. Pour concevoir la première technique, nous analysons l'impact de l'orientation et de la longueur d'un curseur tangible sur les performances de l'interaction à une seule main. Pour concevoir la deuxième technique, nous analysons les performances d'un curseur tangible extensible qui permet de repositionner le

pouce au sein de sa zone de confort. Pour concevoir la troisième technique, nous analysons les performances d'un curseur tangible émergeant devant ou derrière l'écran, permettant d'élargir la zone d'interaction à la zone de confort de l'index derrière l'écran lorsque le pouce atteint les limites de sa zone de confort devant l'écran.

Sur la base des résultats de sept expériences différentes, nous suggérons que :

1. un curseur tangible conventionnel offre de bonnes performances mais nécessite des changements de prise en main lors de l'acquisition des cibles à une distance de 70 mm.
2. un curseur tangible émergeant devant ou derrière l'écran offre de bonnes performances et un prise en main stable lors de l'acquisition des cibles à une distance de 100 mm.
3. un curseur tangible extensible offre de bonnes performances et un prise en main stable lors de l'acquisition des cibles à une distance de 200 mm.

De plus, les expériences effectuées ont permis l'exploration d'un aspect peu étudié des interfaces tangibles qui changent de forme : la manipulation pendant le changement de forme. Nos études montrent comment différentes caractéristiques de conception du changement de forme, comme l'orientation et l'amplitude, peuvent avoir une incidence sur l'interaction.

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Publications

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- Juan Rosso, Céline Coutrix, Matt Jones, and Laurence Nigay. 2017. Deformable tangible slider for eyes-free one-handed thumb interaction on mobile devices. In *Proceedings of the 29th conférence francophone sur l'Interaction Homme-Machine (IHM '17)*. ACM, pages 21-31.
- Juan Rosso, Céline Coutrix, Matt Jones, and Laurence Nigay. 2018. Simulating an extendable tangible slider for eyes-free one-handed interaction on mobile devices. In *Proceedings of the 2018 International Conference on Advanced Visual Interfaces (AVI '18)*. ACM, Article 16, 9 pages.

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- Simon Robinson, Céline Coutrix, Jennifer Pearson, Juan Rosso, Matheus Fernandes Torquato, Laurence Nigay, and Matt Jones. 2016. Emergeables: Deformable Displays for Continuous Eyes-Free Mobile Interaction. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, pages 3793-3805.

¹See <http://www.fitlab.eu>

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Chapter 1

Introduction

Mobile devices have become an essential device for our everyday activities. Modern smartphones and tablets enable users to perform tasks that, in the past, were only possible to fulfill on desktop computers. For instance, smartphone users can check their emails, geo-localize themselves in real-time on a map, play video games, and create documents with a text processor. Furthermore, the portable aspect of such devices allows users to take it with them anywhere. This has impacted the preference of users towards mobile devices, which is reflected in the current consumption trend: a market study [74] reported that the PC market shrank 5.7% between 2015 and 2016, with a total shipment of 260 million units. On the contrary, a market study [75] reported a growth of 2.5% in the smartphone market, with a total shipment of 1,451 million units. The relevance of mobile devices is also reflected in the number of users. Android alone holds a market of 2 billion users [51] (considering tablets and smartphones), hence, usability problems with such devices are very important to solve.

In the domain of Human-Computer Interaction (HCI), this doctoral study is dedicated to interaction with such mobile devices. In particular we focus on two major problems:

- **The visual attention required to operate mobile devices:** since the introduction of touchscreens, mobile interaction mostly relies on direct manipulation

with the fingers on a flat touchscreen surface to manipulate elements of a graphical user interface. The lack of haptic feedback caused by flat touchscreens have forced users to look at their devices in order to interact with elements displayed on the screen. Such a visual dependency becomes problematic and even fatal in situations where the user must focus her/his visual attention somewhere else, for instance, while talking to a person or when crossing a street. This problem is studied in the HCI domain and researchers use the term *eyes-free interaction* to refer to operation of the mobile device without looking at it.

- **The operation of the mobile device with a single hand:** there are situations in which operation with a single hand is required (e.g., writing on paper information obtained on the mobile device or carrying a grocery bag while checking the schedule of the bus). Despite this, modern mobile devices are difficult to operate with a single hand due to the current tendency to increase the size of the touchscreen. As a consequence, users cannot reach the whole area of the touchscreen with their thumbs. Using both hands to interact with the mobile device would solve this issue. However, previous studies have shown that users prefer operating the mobile devices with a single hand [71, 85]. Several research studies focus on the issue and researchers use the term *one-handed interaction* to refer to operation of the mobile device with a single hand.

This doctoral research focuses on these two issues, namely, *eyes-free one-handed interaction*. This is a vast research subject and we focus it to the case of continuous controls, and in particular, interaction with sliders on mobile devices. Adjusting continuous parameters with sliders on mobile devices is a common task both in a professional environment (e.g., audio engineers fixing the sound volume of a venue before a concert [88], and scientists filtering data displayed on a wall-sized display [80]) and in a domestic environment (e.g., a person at home adjusting the speaker's sound volume [18] or the lamp's light color [130]). Although some other solutions allow users to select a value among a continuous range of values (e.g., through the finger's orientation [114] or pressure on the screen [152], or by using other widgets

such as rotary dials and thumbwheels), this doctoral work focuses on sliders due to retro-compatibility purposes. A recent study [88] shows that lead users (see [176]) of sliders, such as audio engineers and graphic designers, prefer leveraging their expertise with familiar interfaces and controls even if other solutions could be more beneficial in the long term.

The following scenario (further discussed in Chapter 2) illustrates the need that some lead users of sliders have of operating sliders on a mobile device in a one-handed manner while being eyes-free: *Bob is the audio engineer of a band that will perform live on an open venue. Bob is in charge of adjusting the volume level of the instruments coming out from the different speakers around the venue. For this, Bob uses a static mixing console crowded with large physical sliders positioned in a vertical way. However, the location of the mixing console does not allow Bob to move around the venue looking for weak-sound spots and adjust the instruments' volume, as sometimes they overlap each other. To tackle this issue, Bob makes use of an application on his mobile phone which displays a graphical interface that mimics the physical one of his mixing console. This allows Bob to control the mixing console sliders at distance. At the same time, Bob needs to communicate with musicians at distance to test the sound of each instrument at different locations around the venue. Bob communicates with the musicians through hand signals. Bob uses one hand to operate his mobile phone and the other hand to communicate. Finally, Bob needs to keep his visual attention on the stage in order to get visual feedback from the musicians.*

Since graphical sliders on mobile devices can be long and commonly positioned in a vertical or horizontal way, reaching all the slider's areas can be problematic when operating a smartphone with a single hand. Moreover, their graphical nature requires the visual attention of the users. This doctoral research addresses these issues with graphical sliders through the design of eyes-free one-handed interaction techniques with sliders on a mobile device.

1.1 Research Goals and Methods

The goal of the conducted research is to improve interaction with sliders on mobile devices. As stated above, interaction with a single hand and the visual attention required by graphical user interfaces are major problems that affect the interaction with mobile devices. In this context, the research question we address is how to improve eyes-free one-handed interaction with a slider on a mobile device. To answer the question, we adopted a two-step approach (see Figure 1-1).

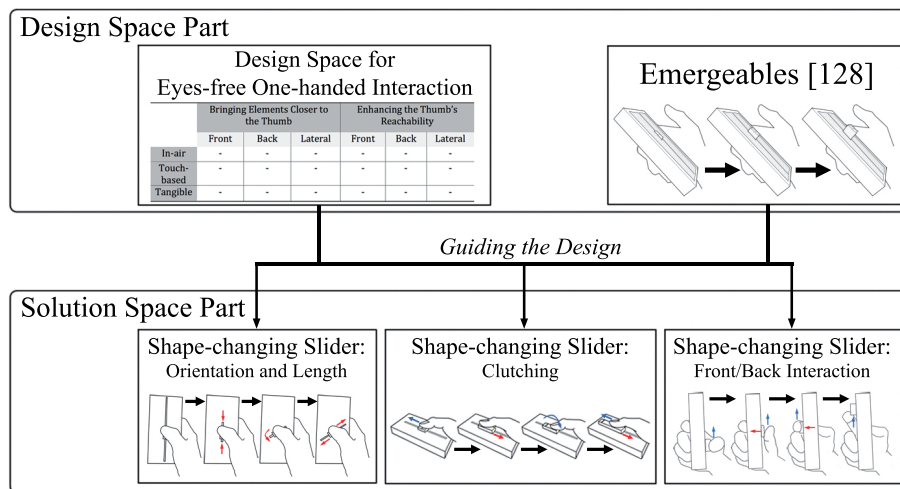


Figure 1-1: The followed research approach: a design space on eyes-free one-handed interaction and the *emergeables* concept [136] were used to guide the design of new solutions for eyes-free one-handed interaction. The techniques change different aspects of the slider, e.g., the knob's location or size, or the slider's orientation or length (direction of the red arrows), to facilitate thumb operation, clutching (direction of the blue arrow) or index finger operation.

First, we establish the foundations for the design of new interaction techniques for eyes-free one-handed interaction on mobile devices. For this, we 1) establish a design space in which we synthesize our review of existing techniques on eyes-free interaction and one-handed interaction. The design space is organized along the set of characteristics that we identify for eyes-free one-handed interaction on mobile devices; and 2) we describe a concept for eyes-free interaction on mobile devices called

*Emergeables*¹ [136] in order to illustrate the mobile device of the future that could support new interaction techniques for eyes-free one-handed interaction.

Second, we validate the ability of the design space to guide the design of new interaction techniques. Three new interaction techniques for eyes-free one-handed interaction were designed based on the aforementioned design space and the *Emergeables* concept which envisions shape-changing mobile devices capable of protruding tangible controls out of the display surface. The techniques rely on shape-changing tangible sliders capable of changing different design properties (e.g., orientation, length and side of the mobile device where it is presented). For each designed technique, we performed experimental evaluations.

1.2 Contributions

In the domain of HCI, this thesis contributes to the domain of mobile interaction and tangible interaction. The key contributions are:

1. A design space for eyes-free one-handed interaction on mobile devices.
2. The design and evaluation of three interaction techniques for eyes-free one-handed interaction of sliders on mobile devices.

Our first contribution, is a design space for eyes-free one-handed interaction on mobile devices. The design space is structured around three main properties derived from the existing work in the literature: 1) the strategy used to facilitate one-handed interaction, 2) the approach used to support eyes-free interaction, and 3) the side of the mobile device where the interaction takes place. This design space serves for guiding the design of eyes-free one-handed interaction techniques. We used this design space for the design of the contributions we will present in Chapter 5 and 6.

¹We want to clarify that the author of this thesis was not the main author of the *Emergeables* concept [136]. However, he was part of the research team in which he designed and developed the high-resolution prototype, and was also involved in the analysis of the collected data from the experiment.

Our second contribution includes three new techniques that are based on the *Emergeables* concept [136] and were designed according to the previously presented design space (see Figure 1-1). The techniques rely on shape-changing tangible sliders capable of changing different design properties in order to facilitate one-handed interaction.

The first technique aims at facilitating one-handed interaction by changing the orientation and the length of the sliders. In a controlled experiment, four different designs of tangible sliders are tested for a distant pointing task: a large-vertical slider, a large-tilted slider, a small-vertical slider, and a small-tilted slider. The results show that: 1) the orientation of the slider has no influence on performance, and 2) small sliders perform slower in comparison with larger sliders due to their smaller motor scale.

The second technique relies on thumb-clutching movements on an extendable tangible slider to facilitate one-handed interaction while supporting eyes-free interaction. In a first experiment, a large tangible slider knob, which enables thumb-clutching, outperformed direct manipulation with a conventional small tangible slider knob. In a second experiment, we build and evaluate an actuated tangible prototype that supports the benefits of the large knob while improving portability. Results show that thumb-clutching on an actuated prototype outperforms a graphical conventional slider for targets far from the thumb's reach. However, the actuation motion disrupts interaction. In a third experiment we test a new version of the actuated tangible prototype (with a reduced thickness) to study the impact of the actuation motion on eyes-free interaction. Results show that the actuated prototype performs equally well in both blinded and non-blinded conditions and outperforms a graphical extendable slider.

The third technique involves Front- to Back-of-Device interaction with a shape-changing tangible slider. In a first experiment, we evaluate different shape transitions between front and back sides. The goal is to inform the best design that facilitates changing operation from front to back surfaces. Results show that actuation motions perpendicular to the thumb's movement do not disrupt interaction, and an

instant shape transition was preferred over a gradual one. In a second experiment, we compare dual-side (front and back) interaction against thumb-clutching and direct manipulation for reaching targets far from the thumb’s reach. Results show that dual-side interaction outperforms the other conditions while providing a stable handgrip. In a third experiment, we evaluate the same conditions but for reaching targets close to the thumb’s reach. Results show that although a conventional tangible slider outperforms our front-to-back approach, our solution enables a stable handgrip.

1.3 Structure

The document is structured as follows (see Figure 1-2):

- In Chapter 2, we introduce the focus of our study: interaction with sliders in an eyes-free and one-handed manner.

The Part I Design Space is composed of two chapters in which we establish key characteristics for the design of new eyes-free one-handed interaction techniques.

- In Chapter 3, we present a review of the existing techniques for eyes-free and one-handed interaction. We then present our design space, which focuses on eyes-free one-handed interaction.
- In Chapter 4, we present a concept (first introduced in [136]²) for eyes-free interaction with dynamic tangible controls on shape-changing mobile devices. We annexed an experiment we performed to validate the concept’s approach on the manipulation of tangible sliders and dials.

The Part II Solution Space is composed of two chapters describing the interaction techniques we propose for eyes-free one-handed interaction with sliders.

- In Chapter 5, we present four experiments we performed in order to evaluate the performance of two of our techniques, namely, changing the orientation

²the author of this thesis was part of the research team

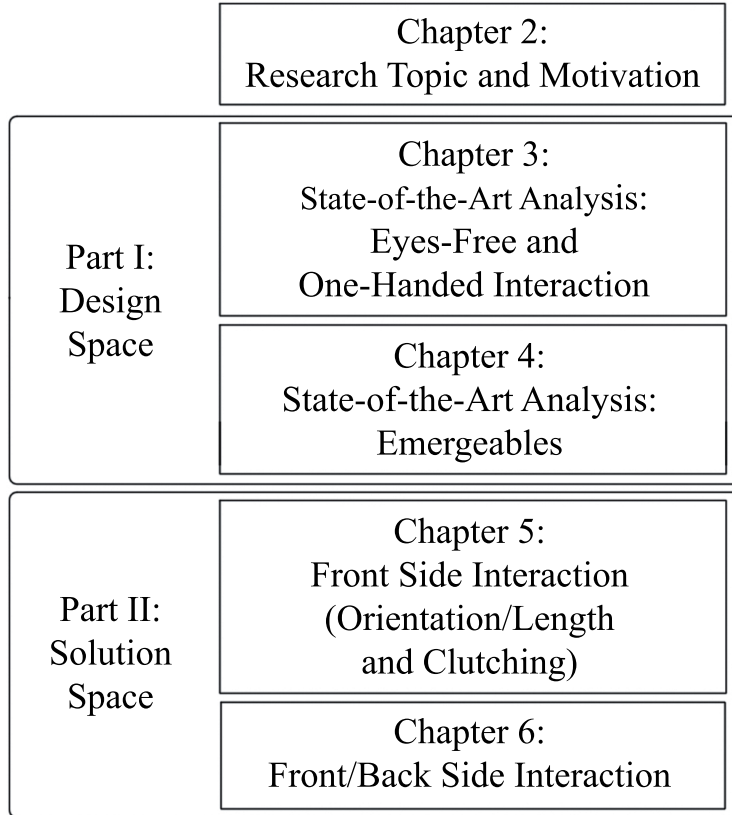


Figure 1-2: Structure of the doctoral work.

and length of sliders and clutching operation with sliders. The techniques are designed for interaction on the front side of the mobile device.

- In Chapter 6, we present three experiments we performed in order to evaluate the performance of our last technique, namely, Front- and Back-of-Device interaction with sliders.

Chapter 2

Research Topic and Motivation

Mobile devices, such as phones and tablets, are the most popular electronic mobile devices since their commercial introduction, reaching a global total of 5 billion mobile subscribers [54]. Current mobile devices allow us to communicate with others, navigate web pages, take pictures and record videos, check our real-time location on maps, play our favorite music and so on. We can interact with these devices while on the go. In this thesis, we will use the definition of *mobile* coined by Rodden *et al.* [137]: “*devices that may be moved by others [users], e.g., carrying around a PDA or wearable computer*”.

Since mobile devices allow us to perform a wide variety of everyday tasks, it is then important to study how people interact with these devices. Such field of study is commonly referred as *mobile interaction*, and its relationship with human-computer interaction can be defined by from Love [109] as follows:

[...] mobile human-computer interaction will be defined as the study of the relationship (interaction) between people and mobile computing systems and applications [...] HCI is concerned with investigating the relationship between people and computer systems and applications.

In this chapter we motivate the conducted research study by describing three key topics related to mobile interaction, namely *eyes-free interaction*, *one-handed interaction* and *sliders*. We will present the relevance and the problems related to these topics. Finally, we conclude the chapter by presenting case scenarios to illustrate

the importance of these topics.

2.1 Eyes-Free Interaction

Modern mobile devices (e.g., smartphones and tablets) adopted touchscreens and graphical user interfaces. Due to the lack of tactile feedback, it is difficult to interact with such interfaces because touchscreens are flat surfaces and only provide visual feedback to the user. This is particularly relevant for situations, like crossing a street or in social settings, that require the user's visual attention. As a consequence, the graphical interface becomes clearly inappropriate (see Figure 2-1). For such scenarios, an approach that minimizes the visual attention required by a mobile device is needed. Such approach is commonly known as *eyes-free interaction*.

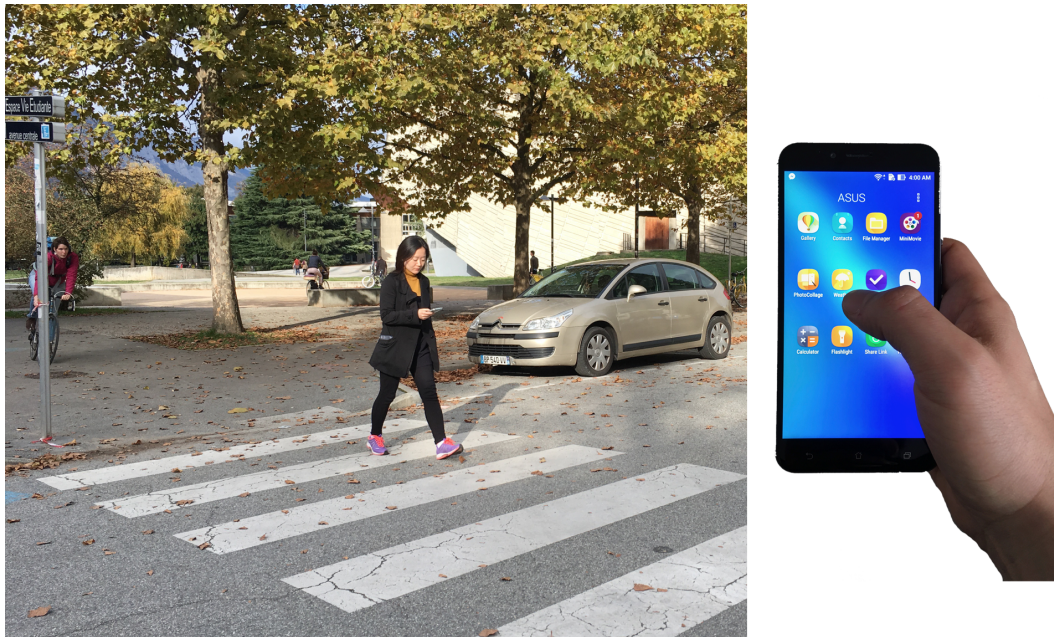


Figure 2-1: Left: Nowadays it is common to see users interacting with their mobile phones while crossing the street. Right: A typical graphical interface on modern mobile phones.

2.1.1 Relevance of Eyes-Free Interaction

A study by Yi *et al.* [187] explored the main motivations that drive users to manipulate their mobile devices in an eyes-free manner. Authors made use of two orthogonal axes to define the categories for the common user motivations (Table 2.1):

	HUMAN	PHYSICAL
CONTEXTUAL	Social	Environmental
	Motivation 1: Foster social respect Motivation 2: Avoid interruption to social activities Motivation 3: Protect private information	Motivation 4: Enable operation under extreme lightning conditions Motivation 5: Improve safety in task switching
INDEPENDENT	Personal	Device features
	Motivation 6: Entertainment Motivation 7: Self desire of self-expression Motivation 8: Lower perceived effort	Motivation 9: Enable operation with no/small screen Motivation 10: Enable multitasking on the same device Motivation 11: Enable distant interaction

Table 2.1: Categorization of common user motivations for eyes-free interaction from [187]: based on two dimensions (*contextual* vs. *independent*; *human* vs. *physical*), motivations were sorted into four categories (social, environmental, personal, and device features).

1. the context dependency, which can be either:
 - independent, this is, motivations are triggered by a factor related to users' preferences;
 - or contextual, this is, motivations are triggered by an external factor.

2. the realm, which can be either:

- physical, this is, motivations are triggered by a factor of the physical environment;
- or human, this is, motivations are triggered by a human factor, either by the user her/himself or by others.

Four categories are described as the result of crossing these two dimensions:

- **Social:** in some situations, looking at the mobile device could be socially inappropriate, interrupt a group activity or raise privacy concerns. For instance, in some social settings, looking at the mobile device could be disrespectful, for instance, while talking to others, looking at the mobile phone could be perceived as impolite. Looking at the mobile device could interrupt the user from following a social activity. For instance, looking at the number of an incoming call while watching a football match with friends.

In some situations, users would rather focus their visual attention on the social activity. Moreover, users could interact with their mobile device in an eyes-free manner for protecting privacy. For instance, to make sure their password is not being seen by someone else.

- **Environmental:** the characteristics of the environment could interfere or prevent users from looking at their mobile devices. For instance, physical conditions of the environment could prevent users from looking at the screen. For instance, direct sunlight often makes the screen unreadable.

Furthermore, elements in the environment could represent a hazard to the user's safety and thus prevent them from looking at the screen. For instance, switching visual attention between the mobile device and the road while crossing a street (see Figure 2-1).

- **Personal:** eye-free interaction could also be motivated by personal factors. For instance, for some users, operating their mobile phones in an eyes-free manner gives them a feeling of self-accomplishment. The satisfaction comes from succeeding at the unusual experience. For instance, a participant from Yi *et al.*'s

study [187] commented, “*I can experience very different things when I am using eyes-free interaction. I think I am very good if I can succeed*”.

Some users interact with their mobile device in such way to self-express themselves in front of others. Some users perceived eyes-free interaction as less cognitively/physically demanding than when focusing their visual attention on the device. For instance, a participant from Yi *et al.*'s study [187] commented, “*When I enter the library, I need to switch my phone to silent mode. But it's troublesome to take the phone out. So I like to do it in my pocket without looking at the phone*”.

- **Device features:** in some situations, eyes-free interaction is desired due to physical constraints from the device itself. For instance, graphical interfaces of devices designed with small screens could be challenging to look at and interact with (e.g., smartwatches and portable MP3 players like [140]). In addition, multitasking on a mobile device could restrict eyes-free interaction. For instance, when walking and talking to a person on the phone, checking for battery level requires users to switch their visual attention between the user's surroundings and the device.

The motivations described above are related to cases in which the display space (where the result of the performed task is displayed) and the motor space (where the task is performed) are coupled. However, there are cases where the control space is decoupled from the display space (e.g., controlling an appliance at distance [80]). For such cases, eyes-free interaction is required for users to focus their visual attention on distant display space. With the increasing power and wireless connection capabilities of mobile devices and the popularization of mobile applications, several appliances have released mobile applications that allow interaction at distance. For instance:

- TV applications (e.g., [164]) allow users to focus their visual attention on the TV screen while using their mobile device to interact with it;

- several commercial drones can be operated with a mobile device through specialized applications (e.g., [150]);
- some mobile applications allow users to start/stop the engine of their vehicles with their mobile phones (e.g., [33]);
- current smart home applications allow users to control several household appliances, such as locks, lights, and temperature (e.g., [156]).

To conclude, several motivations for eyes-free interaction are identified for various situations. When eyes-free interaction is not provided, it can lead to problems that we will present now.

2.1.2 Problems Caused by the Lack of Eyes-Free Interaction

There are several situations in which the lack of eyes-free interaction could be a problem for users. For instance, when checking emails while walking on the street; setting the home's temperature while driving. The visual attention required to operate a mobile device could interrupt users from performing a task and could be dangerous for the user's safety.

2.1.2.1 Task Interruption

The visual dependency required by graphical user interfaces on mobile devices could be problematic for users when performing tasks that require focusing on a distant point of interest (e.g., audio engineers operating graphical sliders while keeping their visual attention on the stage [88]). For such situations, users would then need to shift their visual attention between the screen of the mobile device and the point of interest. Such an interruption of the user's visual attention has a negative impact on the performance, for example, for distant pointing tasks [80, 107]. For professionals that work under pressure, a slow performance time could be problematic and, ultimately, cause health issues. For instance, stress on audio engineers have been linked to working under pressure [173].

2.1.2.2 User's Safety

The visual attention required by graphical user interfaces on mobile devices reduces the awareness of the surroundings. In situations like driving or crossing a street, this could be dangerous or even fatal.

2.1.2.2.1 On the Road Worldwide, per year, nearly 1.3 million people die in road crashes, and 20 to 50 million are injured or disabled. This makes road traffic crashes the 9th leading cause of death and accounts for 2.2% of all deaths globally [48]. Lipovac *et al.* [105] recently published a review of the literature about the effects of mobile phones use while driving. The study analyzes the results about the negative impact of mobile phone use while driving from 60 published studies between 1994 and 2013. The study summarizes a list of negative findings related to the usage of mobile phones while driving. Such findings confirm the connection between mobile phone use and driving performance. We present the most relevant findings on the use of mobile phones while driving:

- Among the main reasons why drivers use their mobile phone while driving, a study from Hallett *et al.* [58] with 1057 interviewees found out that, respondents were reading (66.2%) and typing (52.3%) text messages at least 1 to 5 messages per week, while driving.
- Looking at the mobile phone while driving in order to read, reply or send text messages has been recognized as a behavior that is riskier than having a conversation on the phone [6].
- The mobile phone use while driving has proven to increase the cognitive workload. This translates into an increased reaction time when obstacles appear on the road [96, 154, 27]. Such a result could reduce the time until collision and thus decrease the chances of avoiding an accident.

2.1.2.2.2 For Pedestrians A study by Nasar & Troyer revealed that, only in the US, the number of pedestrian injuries related to mobile phones has increased through

the years, reaching a total of 1506 in 2010 [118]. Furthermore, authors speculate that the actual number of injuries is much higher since many injured people might not have reported the accident as related to the mobile phone use.

Mobile devices have influenced the behavior of pedestrians while moving. Existing studies found out that:

- looking at mobile phones reduces the awareness of the situation and distracts her/his attention [73, 151];
- unintentional blindness, slower walk and a more frequent change of direction are observable on pedestrians interacting with their mobile phones [73];
- texting with a mobile phone increases the chances of being hit by a car when crossing a street [142].

2.1.3 Summary of Eyes-Free Interaction

Current mobile devices allow interaction through touchscreens. The displayed graphical user interfaces demands visual attention. This prevents users from being eyes-free, which is a desired feature in a wide range of scenarios and situations. For instance, there are situations in which eyes-free interaction is needed in order to operate a distant appliance (i.e. the output of the controlled system is external to the mobile device). In some professional domains, this type of interaction is crucial to execute a task (e.g., audio and light engineers adjusting audio/light parameters while looking at the performers [88], scientists analyzing data displayed on a wall-size display [80]). This highlights the relevance that eyes-free interaction has on the daily activities of some professionals.

Eyes-free interaction can also have an impact on the user's safety. Existing studies have shown that the visual dependency of graphical user interfaces on mobile devices can increase the cognitive workload [96, 154, 27] and reduce the sense of awareness and attention [73, 151]. In some situations (e.g., using a mobile phone while driving or crossing a street) the required visual dependency caused accidents or even deaths [119].

Finally, eyes-free interaction is desired due to personal motivations. For instance, a self-achieving feeling of operation the mobile device without looking at it, or to show respect to other persons in a social setting.

In this section we have introduced a major research topic related to mobile interaction, this is eyes-free interaction. We have reviewed its relevance. In the following section, we will introduce another major topic in mobile interaction, this is, interaction with mobile devices with a single hand.

2.2 One-Handed Interaction

According to a study by Hooper [71], based on the data from 780 persons, there are three basic ways how users hold their mobile devices while interacting with them (see Figure 2-2): holding and interacting with both hands simultaneously; holding it with one hand and using the other hand to interact with it; and holding it with only one hand and using the thumb to interact with it. Interaction with the same hand that holds the mobile device is commonly known as *one-handed interaction*.

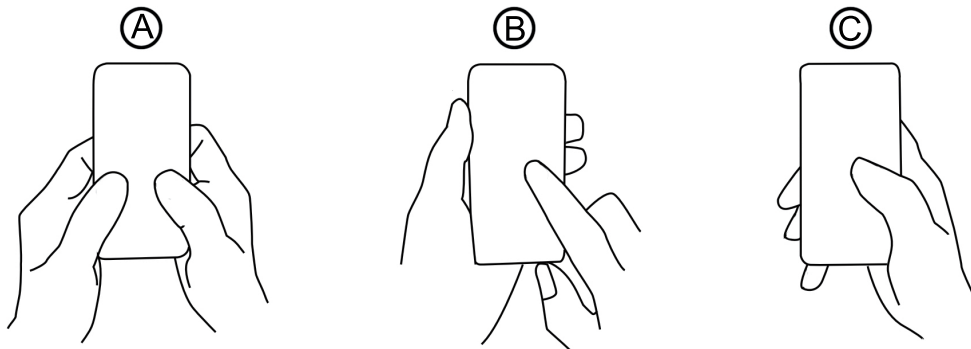


Figure 2-2: Common handgrips on mobile devices: (A) holding and interacting with both hands simultaneously; (B) holding it with one hand and using the other hand to interact with it; and (C) holding it with only one hand and using the thumb to interact with it.

2.2.1 Relevance of One-Handed Interaction

Several reasons may lead users to operate their mobile devices with only one hand, for instance, preference or encumbrance of the non-dominant hand. A field study by Karlson *et al.* [85] observed how 50 users interacted with their mobile devices at the airport. They reported that 45% of participants used one hand and only 19% used two hands. Authors also ran an online survey on users' interaction preferences. They found that 66% of users prefer using one hand and only 9% prefer using both hands. Furthermore, in a mobile context, other activities may also require the user's attention, like crossing a street or carrying shopping bags.

Girouard *et al.* [49] conducted an online survey of one-handed usage patterns on mobile phones. 158 persons participated in the survey. Results showed that 70.89% the participants prefer to use their mobile phones with their dominant hand. Also, participants indicated that they use their mobile devices with a single hand in a diversity of scenarios: 48.10% while walking, 43.04% while standing, 32.38% while sitting, 24.68% while the phone is resting on a surface (both arms on the table), and 31.65% without any preference. This suggests a clear preference towards one-handed interaction in different everyday life situations. The survey also provided explanations for using one-handed interaction from 105 participants. Among the reasons to use only one hand, participants commented that using one hand provokes less occlusion of the screen than using two hands, using one hand is more comfortable than using two hands, and that actions required to operate the phone usually can be achieved with only one hand. One-third of these participants stated that they would use their mobile phone with one hand for their safety (e.g., breaking the fall with the free hand in case of falls, trips or slides). Finally, the survey revealed the tasks most commonly performed with only one hand: unlocking the phone (81.65%), selecting an app (77.85%), scrolling through websites (75.95%), and viewing pictures (73.42%). This suggests that one-handed interaction is preferred to perform many of the day-to-day tasks on mobile devices. However, other factors, such as encumbrance [120], could incite users to perform other tasks on the mobile device in a one-handed manner.

Similarly, some professionals, such as audio engineers, face situations in which they need to manipulate their mobile device with a single hand; for instance, performing hand signals to communicate with musicians on stage with one hand while operating a graphical slider on a mobile device with the other hand (see Section 2.4.1).

While there are numerous ways in which users can hold their mobile device with only one hand, placing the device in the palm with fingers on the sides is considered the most practical to limit usability issues [12]. Such hand position allows the thumb (the only available finger to interact with the touchscreen) to cover as much area of the screen as possible. However, due to the limited range of movement of the thumb, one-handed interaction poses usability issues to users.

2.2.2 Problems Caused by One-Handed Interaction

For a better understanding of the limitations of thumb-based one-handed interaction on mobile devices, it is necessary to understand the structure and biomechanical principles of the hand, and particularly of the thumb.

2.2.2.1 Limited Range of Motion of the Thumb

The thumb is used in a wide variety of human tasks that require the manipulation of physical elements in our environment (e.g., grasping a mobile phone). The development of an opposable thumb constitutes a major factor in the evolution of the hand [83]. Indeed, it provided humans with a remarkable increase in the versatility of the hand function [83]. The thumb supports flexion/extension, palmar adduction/abduction, and radial adduction/abduction movements (see Figure 2-3). Such movements are possible due to the kinetic chain formed by the fingers' joints and joint articulations [12].

Researchers have studied several methods to model the range of motion of such joints of the fingers. We will now describe some of these methods. The simplest method to evaluate the flexion motion is by linear measurement of the distance from the fingertip to the distal palmar crease (see Figure 2-4) [20]. However, this method

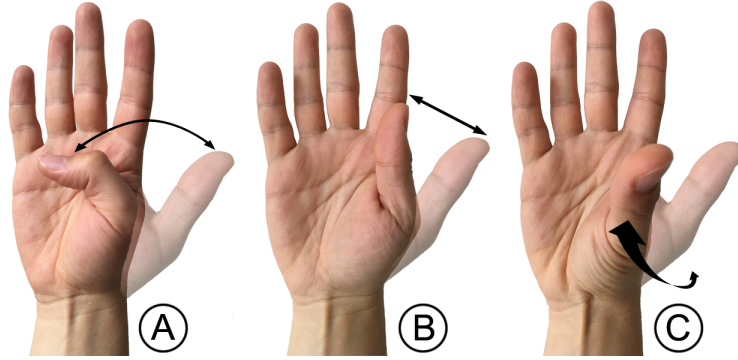


Figure 2-3: Terminology used for joint motions [12]: A) flexion and extension; B) palmar adduction and abduction; C) radial adduction and abduction.

cannot determine the range of motion of each joint.

Goniometers (devices used to measure joint angles or range-of-motion in degrees) is another method which has been widely used to evaluate the fingers' performance, particularly the flexion motion [155].

Finger dynamography is a method that produces a graphic record of the movement. The shape of the motion can be evaluated to determine motor problems. The method requires participants to attempt four finger postures of the proximal interphalangeal (PIP), and metacarpophalangeal (MCP) joints (see Figure 2-4) [110].

Researchers have also used three-dimensional (3D) geometrical methods and biomechanical modeling to measure the maximal and active workspace of the thumb motion [95, 157, 190].

Regarding the functional area of the thumb (see Figure 2-5), some methods have made use of markers on a surface and a video motion analysis system to evaluate the maximal 2D functional area of the hand [29, 30]. The functional area is defined as the closed curve formed by the tracking of the fingertip while performing five digital postures proposed by Chiu's work [29, 30]. This method provided the area of the actual maximal motion space of the assessed finger, such as the thumb.

These studies highlight the limitations that the anatomy of the hand poses on the range of movement of the thumb. In the following section, we study these limitations of the thumb's movements affect the interaction with a mobile device when used with

a single hand.

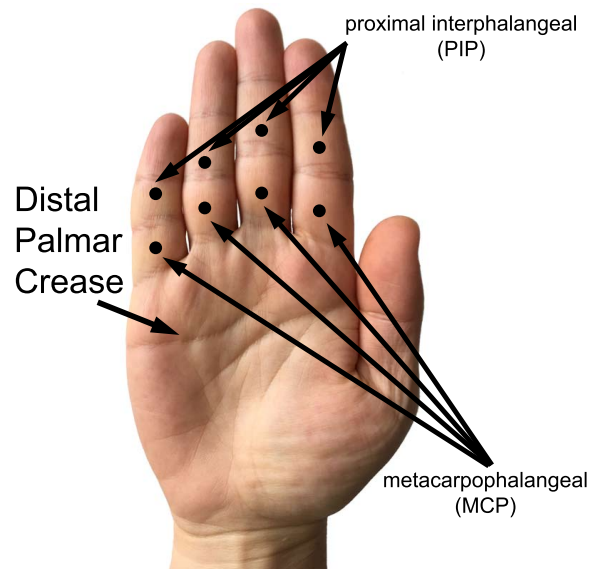


Figure 2-4: Representation of the distal palmar crease, proximal interphalangeal (PIP), and metacarpophalangeal (MCP) joints in the hand.

2.2.2.2 Impact on Interaction: Thumb Reachability

The thumb is commonly used to interact with a mobile device when holding it with a single hand. It is then important to identify the limitations of the thumb's range of movement on mobile devices. We will now present studies regarding the limitations of thumb interaction with mobile devices under three categories: the limitations on thumb's performance, limitations on thumb's reachability and limitations by thumb's ergonomics.

2.2.2.2.1 Limitations on Thumb's Performance Studies have demonstrated the limitations of thumb interaction on mobile devices in terms of performance. For instance, an empirical study by Karlson *et al.* [85] demonstrated that areas difficult to reach with the thumb provoke a significant slowdown (between 7% and 12%) in movement time. Based on this, authors introduced three levels of perceived difficulty to reach areas with the thumb: easy, medium and hard. Perry & Hourcade [129]

extended the work of Karlson *et al.* [85] by evaluating thumb-based one-handed interaction while walking. Results show that users do not prefer selecting targets that are located near the borders of the mobile device, as they were found difficult to select. The results also show no significant difference in performance between walking at a normal pace and standing.

The direction of the thumb’s movement affects the speed and performance for pointing tasks: A study by Wobbrock *et al.* [179] showed that horizontal movements performed with the thumb on the front surface of a mobile device are faster (0.11s) than vertical ones for distances ranging from 9mm to 36mm. Furthermore, the hand-grip selected by the user could affect motor performance and musculoskeletal strain [56]. For instance, for one-handed interaction, if the thumb is involved in the interaction with the device and with the device’s stability, then these two functions may conflict and decrease performance. Moreover, the functional area of the thumb is limited with single-handed grips and requires sub-optimal postures for out-of-reach areas.

The aforementioned studies revealed the impact that thumb interaction has on performance. Because of this findings, researchers focused on defining the range of motion of the thumb when operating a mobile devices.

2.2.2.2.2 Limitations on Thumb’s Reachability Studies have evaluated the thumb’s range of movement with mobile devices. We will present these studies according to the evaluated dimensions of the thumb’s movement.

2.2.2.2.2.1 Two Dimensions: Functional Area These studies present two approaches: heuristic and predictive model.

- Several heuristic estimates of the functional area of the thumb [31, 38, 71, 182] (see Figure 2-5, A) have been proposed when interacting with the thumb of the hand holding the mobile device.
- Bergström-Lehtovirta & Oulasvirta [12] proposed a predictive model to calculate the functional area of the thumb (see Figure 2-5, B). The model takes as

inputs the surface size, the hand size and the position of the index finger on the back of the device. The model gives, as a result, the functional area that is an area under a parabolic curve. Le *et al.* applied the predictive model from Bergström-Lehtovirta & Oulasvirta [12] to the remaining fingers positioned on the back surface of a mobile phone when held with a single hand [98]. The study describes the functional area of the remaining fingers on different sizes of mobile phones and gives insight of operation outside the thumb's functional area with other fingers.

2.2.2.2.2 Three Dimensions: Functional Workspace Thumbs-up [62] makes use of the functional workspace of the thumb (i.e. the 3D space above the screen in which the thumb can comfortably move) to support mid-air interaction with mobile devices (see Figure 2-5, C). Authors analyzed the in-air thumb-reachable space when holding a mobile phone, and suggested plausible usages for such space to tackle one-handed thumb interaction related problems.

The aforementioned studies revealed the area and space in which the thumb can comfortably interact with the mobile device. Other studies focused on evaluating the thumb's ergonomics to improve interaction within the thumb's functional area.



Figure 2-5: Functional area of the thumb according to: (A) heuristic models, and (B) a predictive model. (C) Functional workspace of the thumb. Figure from [31, 38, 71, 182, 62]

2.2.2.2.3 Limitations by Thumb’s Movements Other studies have focused on evaluating the movements of the thumb of the hand that holds the mobile device. For right-handed users:

- The bottom right corner of a mobile phone proves difficult to reach with the thumb of the hand that holds the device [68, 125] (see Figure 2-6).
- The middle area of a mobile phone allows an easy target acquisition and lower transition times between targets [85, 125] (see Figure 2-6).
- Orthogonal thumb movements from the top right to bottom left corner provide better performance than top left to bottom right corner [68, 85, 168].
- When holding a mobile device with a single hand, the rotation angle (i.e. radial adduction/abduction, see Figure 2-3, page 20) of the thumb is 68.1 degrees [67].

Parhi *et al.* [124] evaluated the different target sizes for thumb-based one-handed interaction and recommended a target size of at least 9.2mm for discrete selections and a target size of 9.6mm for continuous targeting. However, modern mobile operating systems display widgets smaller in size and remain highly functional (e.g., a key of an iOS keyboard displayed on an iPhone SE has a size of 4mm × 6mm). Boring *et al.* [17] evaluated the thumb’s contact area as a form of one-handed input. Authors propose this interaction to replace gestures that are difficult to execute with only one hand (e.g., a pinch gesture for zooming in).

A study by Henze *et al.* [66] shows that touch contacts are skewed relative to the targets position across a mobile device’s touchscreen. In order to correct touch offsets, different touch models have been proposed [66, 70] and have proven to increase the accuracy when selecting targets on a mobile device’s touchscreen.

The presented limitations are related to the thumb’s movements and reachability when interacting with mobile devices. However, one-handed interaction also affects the way how users grasp their mobile devices, which also has an impact on interaction.

1	2	3	4	5
6	7	8	9	10
11	12	13	14	15
16	17	18	19	20
21	22	23	24	25

Figure 2-6: Good (in dark gray) and poor (in white) areas of the screen (with a diagonal length of 8.9cm) of a mobile device to reach with the thumb as shown in a study from Park & Han [125]. Figure from [125]

2.2.2.3 Impact on Interaction: Changing the Handgrip

When reaching targets outside the functional area of the thumb, changes in the grasp of the hand that holds the mobile device have been observed [25, 71]. A study by Eardley *et al.* [40] analyzed how users hold a mobile phone with one hand when pressing buttons on different areas of the screen. Authors identified two small movements when reaching targets near the functional area of the thumb: (1) change on the position of the fingers placed on the back of the device, and (2) tilting of the mobile device within the hand. We will refer to these movements as a *handgrip change* (see Figure 2-7, B). These changes of handgrip enable users to move the functional area of the thumb along the device.

When handgrip changes are not sufficient to reach a target, a shifting of the device within the hand is observable [71]. We will refer to the shift of the device as a *hand relocation* (see Figure 2-7, C).

Such hand movements (i.e. handgrip changes and hand relocations) can be uncomfortable and unstable: a correlation between handgrip changes and the perception

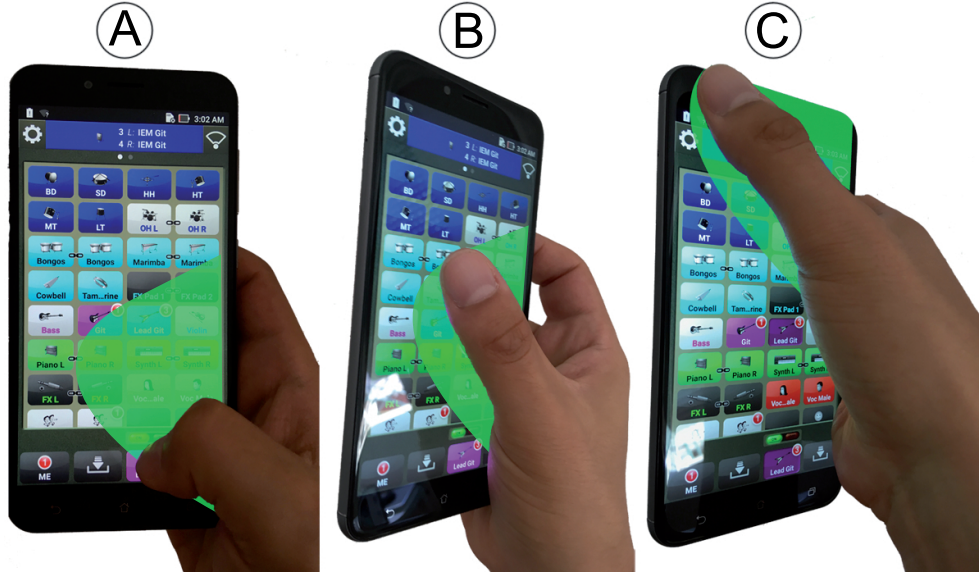


Figure 2-7: Hand movements required to reach targets outside the thumb’s functional area (in green, inspired by the predictive model from Bergström-Lehtovirta & Oulasvirta [12]): (A) Initial handgrip, (B) Handgrip change, (C) hand relocation.

of security (i.e. risk of device being dropped) was experimentally observed for different body postures in [41]. For instance, interacting with a mobile phone while lying down presented the highest amount of handgrip changes and was perceived as the less safe position in comparison with standing and sitting. Furthermore, mobile situations increase the hand oscillation [13], which could ultimately make the user drop the device if it is not being held properly.

To avoid such hand movements and facilitate one-handed interaction, several interaction techniques [84, 89, 100, 102, 138, 177, 188] have been proposed. This is particularly important since modern mobile devices are increasing in size leading to users performing handgrip changes/hand relocations more often [25], and thus, a better understanding of interaction outside the thumb’s functional area is needed.

2.2.3 Summary of One-Handed Interaction

One-handed interaction is the most common way to interact with mobile devices. Unavailability of one of the hands (e.g., carrying a grocery shopping bag) is a common

situation that leads users to one-handed interaction. Furthermore, existing studies reported that avoiding visual occlusion and comfort are also among the main reasons that motivate users to operate their mobile devices with a single hand.

When using a single hand to operate a mobile device, the thumb is the most commonly used finger to interact with the device. However, due to the hand's anatomy, the thumb's range of movement is limited. Researchers have studied the thumb's limitations when interacting with mobile devices, aiming to establish design guidelines to facilitate one-handed interaction.

However, the current trend on mobile devices is pushing towards bigger screens. This ultimately impacts one-handed interaction since the thumb's functional area is not large enough to cover all the surface area of modern mobile devices. Users then need to perform handgrip changes and hand relocations to interact with out-of-reach areas. Such hand movements can be uncomfortable and could make the device slip off the user's hand.

Due to the relevance of one-handed interaction on mobile devices and the limited reachability of the thumb,

In this section we have introduced a major topic related to mobile interaction, this is one-handed interaction. We have reviewed its relevance and its limitations on interaction. Later in this thesis, different approaches to facilitate one-handed interaction will be presented (see Chapter 3). In the following section, we will focus on one-handed interaction with a slider.

2.3 Sliders

Nowadays, graphical sliders on mobile devices are used for a variety of applications. For instance:

- Adjustment of audio and light parameters on mixing consoles.
- Dynamic queries on visual exploration tasks of datasets.

- Mobile devices' parameters adjustment such as sound volume and screen brightness.
- Control of distant appliances such as home temperature and lamps.

As a consequence, in this thesis, we will focus on sliders.

2.3.1 Relevance of Sliders

Mobile devices (e.g., phones and tablets) make use of graphical user interfaces and touchscreens to enable interaction. On such devices, graphical sliders are controlled with a dragging gesture on the knob. Sliders are often used for the mobile device's adjustment of intensity levels, such as brightness, volume, or color saturation. All the main operating systems for mobile devices (i.e. iOS, Android, Windows phone) make use of graphical sliders to control parameters, such as the sound volume of the speaker and the brightness level of the screen. By considering that Android alone holds a market of 2 billion users [51], we can assume the standardization of graphical sliders to control these parameters.

Graphical sliders are also used for the adjustment of parameters of services. For instance, filtering data: the Airbnb application [2] makes use of a range graphical slider (i.e. a double knobbed slider) to specify the price range that a person is willing to pay for accommodation (see Figure 2-8, A). Similarly, current dating applications (e.g., Tinder, Bumble) make use of graphical sliders to filter the search of potential partners (see Figure 2-8, B). Another common usage of graphical sliders is for navigation. For instance, when playing videos on mobile devices, graphical sliders are used to navigate throughout the video quickly. Sliders provide visual feedback about the length of the video and the remaining video time (see Figure 2-8, C). Graphical sliders are also commonly used as Visual Analog Scales (VAS), such as likert scales, to provide user's feedback of a service or a product. Matejka *et al.* [112], studied the effect that the visual representation of sliders as VAS has on performance. The study shows that decorations, such as ticks or labels, along the slider considerably bias the distribution of the selected value.

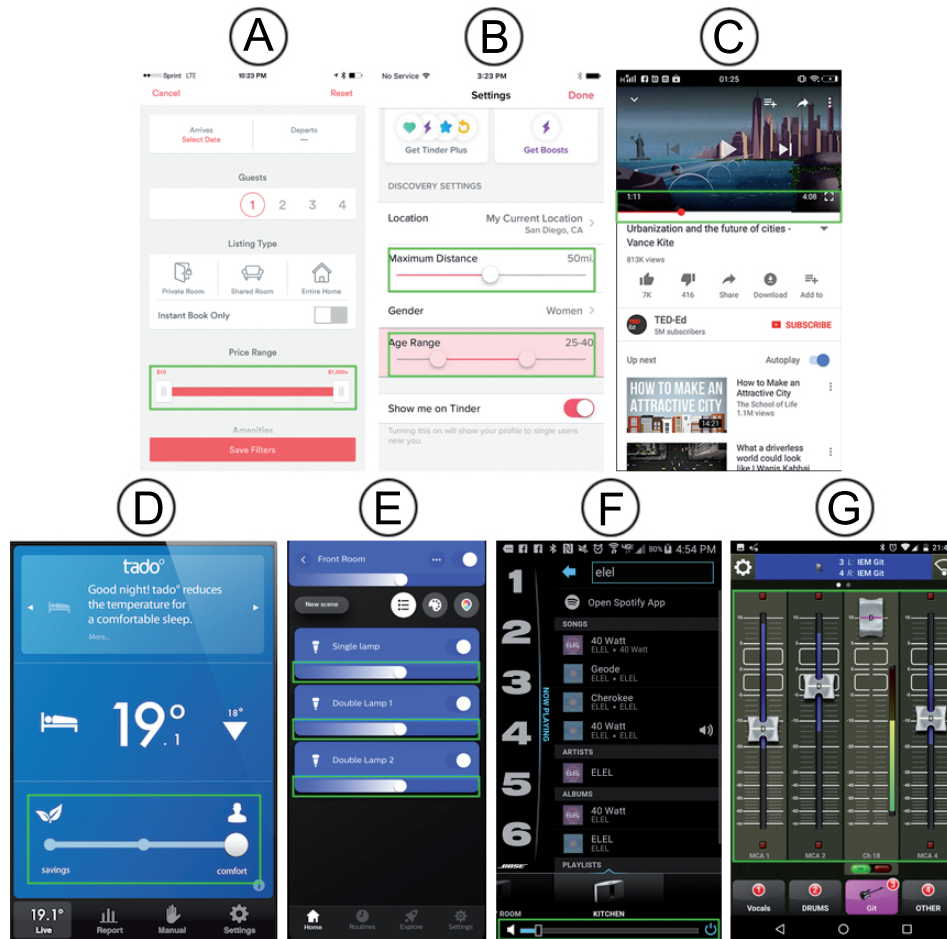


Figure 2-8: Examples of graphical sliders (highlighted in green rectangles) on commercial mobile applications: (A) Airbnb [2], (B) Tinder [165], (C) YouTube [52], (D) Tado [161], (E) Philips Hue [130], (F) SoundTouch [18], (G) X32Q [11].

Graphical sliders are also used for the control of appliances at a distance. Users can control stationary appliances without being in situ, far away through internet. Current smart home applications like Tado [161] enable users to control the temperature at home through graphical sliders at a distance (see Figure 2-8, D). Similarly, Philips Hue app [130] enables users not only to switch on/off lamps at home but also to control the brightness and color through different graphical sliders (see Figure 2-8, E). The SoundTouch app [18] enables users to control the sound volume coming from portable speakers with a graphical slider (see Figure 2-8, F). Manufacturers of mixing consoles offer Digital Audio Workstations (DAWs) for tablets and smartphones

[11, 183] (see Figure 2-8, G). Mobile DAWs make use of graphical sliders to replicate the layout of a stationary mixing console in order to control sound's parameters. Mobile DAWs became relevant since the location of mixing consoles might not be optimal, this is, testing the sound coming from the loudspeakers. The current available mobile solutions allow audio engineers to move around the venue while performing a sound check task previous to a live performance. Moreover, these graphical solutions allow audio engineers to place themselves at locations where they could easily communicate with musicians, for instance, on stage.

2.3.2 Problems Encountered on Sliders on Mobile Devices

Due to the popularity of graphical sliders on mobile devices, their design has been an important issue for mobile interaction, particularly regarding usability. Usability issues include: 1) the lack of tactile feedback on touchscreens, thus forcing the user to look at the screen to operate the slider, and 2) the occlusion of the slider knob due to the operating finger. These issues have led the industry to define design guidelines for graphical sliders.



Figure 2-9: Google's design guidelines for different states of a graphical slider. When unused (normal), the slider presents a small sized knob. When being used (focused and click), the knob increases its size. When the slider is unavailable (disabled), the knob becomes very small.

Google's Material Design [50] proposes design guidelines for the visuals of graph-

ical sliders at different states (e.g., normal, focused, click, and disabled). Following these guidelines, Android-powered mobile devices present a small slider knob when not in use (see Figure 2-9, top). When the knob is touched and being used, it increases its size in order to avoid occlusion problems (see Figure 2-9, middle-top and middle-bottom).

Regarding the positioning of the slider, on mobile devices, sliders are commonly positioned in a vertical or horizontal way. For instance, on Android and iOS operating systems, the sliders to control the screen brightness or the speaker sound volume are presented in a horizontal way (see Figure 2-10). The slider can have a maximum length equal to the width of the screen, which is much smaller than the device's height (e.g., the iPhone X has a width of 70.9 mm and a height of 143.6 mm [4]). As a consequence, when the slider is positioned horizontally, the motor space to operate the slider is small (i.e. small target's size in the motor space). This has a negative impact on usability [26, 35], in particular decreasing performance.

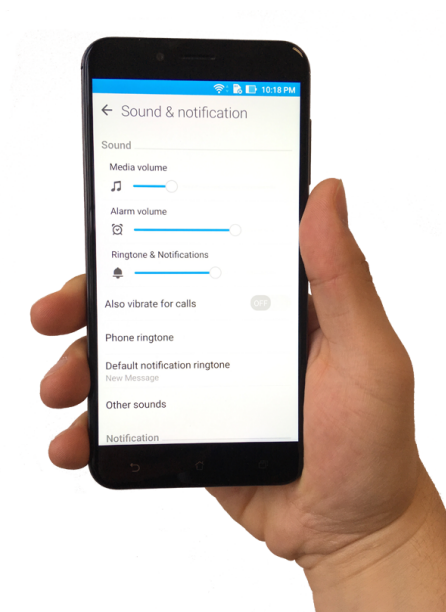


Figure 2-10: Android operating system present horizontal sliders to control audio parameters on mobile devices.

Some mobile applications make use of vertically positioned sliders that offer a larger motor scale (see Figure 2-11, A). This allows users to perform more precise adjustment of the parameter being controlled [26]. However, such a design proves to be a problem when sliders are operated with a single hand. Indeed, long sliders could be difficult to manipulate due to the limitations of the thumb's movement: long vertical sliders include areas outside the functional area of the thumb (see Figure 2-11, B-C), making them difficult to reach with the thumb.

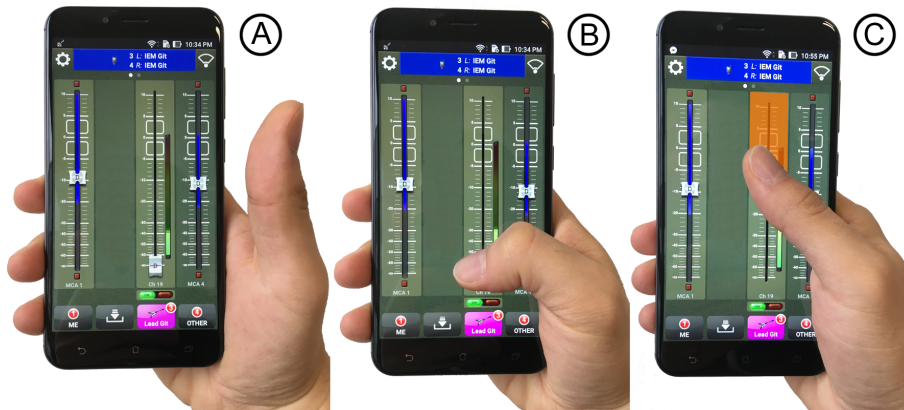


Figure 2-11: A vertical slider from the X32Q [11] application in order to control audio parameters: (A) A vertical long sliders with a large motor scale provides good performance in comparison to small motor scale [26]; (B-C) Due to the limited thumb's range of movement, some areas of the slider could be unreachable (highlighted in orange).

2.3.3 Summary of Sliders

Sliders are widely used as controllers for the adjustment of continuous parameters. Nowadays, graphical sliders are commonly used on mobile devices (e.g., tablets and mobile phones) to control continuous parameters such as the screen brightness or the speaker's sound volume.

However, usability issues are intensified when operating graphical sliders with only one hand on mobile devices. First, the lack of tactile feedback requires users to look at the device's screen to position their thumb on top of the slider's knob.

Second, the operating thumb occludes the slider’s knob. And third, the position of the slider (horizontal or vertical) may define a small motor scale, which could impact its usability (horizontal slider); or, may require operation outside the thumb’s functional area (vertical slider).

In order to address these usability issues, new interaction techniques must be explored to provide tactile feedback for eyes-free interaction, avoid occlusion, and offer a slider with a long motor scale that could be operated from within the thumb’s functional area.

2.4 Case Scenarios

In this section, we will present a real-life case scenario followed by two future case scenarios to illustrate practical examples of *one-handed eyes-free interaction* with a *slider* on a mobile device.

2.4.1 Real-Life Case Scenario: Audio Engineers

To illustrate this case scenario, we conducted online interviews with audio engineers to get feedback about their need for mobile eyes-free one-handed interaction with sliders by considering the task of controlling audio parameters on a venue for a live performance.

In the US alone a study found that there were 117,200 audio engineers in 2014 [123]. Audio engineers are usually responsible for sound check and sound mixing at live performances. For this, they make use of mixing consoles that are composed of several tangible controls (e.g., rotary knobs and sliders). Further, a tangible slider is most commonly used to control the sound volume.

We interviewed ten audio engineers (3 from the USA, 1 from Russia, 2 from France, and 4 from the UK). We have recruited the interviewees through an acquaintance in our social network. We focus on audio engineers since they are experts on manipulation of tangible sliders, hence could be considered as lead users [176]. At first, we asked them to talk openly about their practices and needs when setting up the sound

equipment for a live performance. Then, we asked them to fill a survey (see Appendix A.1 for an example of a filled survey) composed of seven items:

1. Do you find yourself in situations where you need to control sound parameters (e.g., volume, pan) while being away from the mixing console?
2. Do you find yourself in situations where you need to look away from the controls while you are operating them?
3. Do you find yourself in situations where you need both to look away from your mobile device and move around the venue while controlling sound parameters?
4. Do you usually work under tight time schedules to prepare the sound of a venue?
5. Being efficient at adjusting the sound parameters is important for you?
6. Would you consider using a mobile device that can physically mimic the controls of the mixing console?
7. Regarding controls on the mixing console, do you prefer sliders or dials to control the sound volume? Explain why

For each item, the interviewees could answer yes or no. Interviewees were also able to comment their answers. For items 1, 2 and 3, we asked participants to give precise examples of the situations. We present the key user requirements we obtained from these interviews regarding the need of being mobile, eyes-free and one-handed while controlling audio parameters.

2.4.1.1 Being Mobile Is Highly Desired

All of the interviewees agree that being mobile is required when preparing a venue for a live performance. Many of the comments were related to the need of listening to the sound from different points in the venue: “*All venues need the sound to be checked at various positions to get a good ‘average’ of the sound*”; “*One needs to be mobile to get an impression of the way the artist will sound from multiple points in the room*”;

and, “*For situations where we haven’t been able to set up the mixing console in a good position, i.e., where the spectators are*”.

2.4.1.2 Eyes-Free and One-Handed Interaction is Highly Desired

All of the interviewees agree that they prefer being eyes-free from the controls when adjusting audio parameters. Many of the comments were related to the need of receiving visual feedback from performers: “*Taking visual cues from the band usually*”; “*Watching the band for cues*”; and, “*Adjusting monitors for an artist - it’s often easier to watch their expressions/hand gestures than to listen to their responses*”. One interviewee highlighted the importance of being eyes-free from the controls: “*...working and communicating with them [musicians] enable us to build a relationship of trust which is much needed in this field of work*”. The interviewees also commented that in order to communicate with musicians, they require having one hand free. This allows them to communicate through hand gestures or to grab a microphone.

2.4.1.3 Being Efficient With Sliders Is Highly Desired

Finally, we asked if they would be willing to use another widget to control the sound’s volume instead of sliders. All of the interviewees replied negatively. Among the reasons, the interviewees commented: “*Sliders allow you to feel where you are at*”; “*I prefer sliders as I find them quicker to adjust*”; and, “*I prefer physical sliders through habit*”.

Nine of the interviewees agree that being able to efficiently perform on the controls is important. They commented that they usually work under tight time schedules and thus, the efficiency with controls is required.

The interviewees also commented that, nowadays, several mixing consoles could be remotely operated through specialized applications on mobile devices (e.g., [11]) (see Figure 2-11). Nevertheless, these applications are graphical and thus visual attention is required. This not only prevents users from being eyes-free but also affects performance due to the required visual attention [80, 107].

2.4.2 Future Case Scenario: Wall-size Displays

Large screen displays have proven to be beneficial for the exploration of a large amount of data [10, 80, 170], in various application domains including industry, and business [7]. In such settings, users can make use of mobile devices to interact with the displayed data [115, 80]. In the following paragraphs, we will explain how wall-size display settings represent a case scenario that requires mobility, eyes-free interaction, one-handed interaction, and sliders.

2.4.2.1 Being Mobile Is Desired

One of the main benefits that wall-size displays provide is the visualization of large and complex data [10, 80, 170]. Since wall-size displays present information on a large surface, users need to move along the screen in order to explore different parts of the displayed data [10, 106]. Users move closer/further from the screen to get details or an overview of the information space. In consequence, wall-size display users need mobile devices that allow them to move while interacting with the displayed data.

2.4.2.2 Being Eyes-Free Is Desired

Due to the graphical nature of wall-size displays, it is then necessary that users are able to perform tasks in an eyes-free manner in order to look at the display. Attachable tangible sliders [80] have already proven to be a solution for interacting on a mobile device while looking at the wall-size display. However, the presented solution (a set of attachable tangible controls, including tangible sliders) might be unpractical since users would need to carry a set of tangible controls and attach/detach them.

2.4.2.3 One-Handed Interaction is Desired

Wall-size displays are also used to support remote collaborative work. In such setting, users could not only interact with each other through video but also interact with shared on-screen elements. For instance, a user could be pointing at an element on the screen to notify the remote user about it [7, 108]. For cases like data visualization,

a user could change data parameters on her/his mobile device while pointing at an area of interest on the screen. In such situations, one-handed interaction becomes relevant in order to support interaction with the remote user and with the displayed data.

2.4.2.4 Sliders are Desired

For visual exploration tasks such as in information visualization, dynamic queries are used for the exploration of datasets in real-time [80, 170]. Continuous controls, such as sliders, are commonly used for the adjustment of continuous parameters of the data [36, 80, 43, 170] (e.g., time values of a plot). Sliders have been widely used because their guidance matches the number of degrees of freedom of most information visualization tasks which rely on 1-D dynamic queries [1].

2.4.3 Future Case Scenario: Virtual Reality

Virtual reality settings are widely used in different domains. For instance, on video games [147], on workplaces [162], and for commercial purposes (e.g., a website for the design of 3D kitchens [76]). Existing studies have shown the benefits of using mobile devices in virtual environments [87]. In the following paragraphs, we will explain how virtual reality settings represent a case scenario that requires of mobility, eyes-free interaction, one-handed interaction, and sliders.

2.4.3.1 Being Mobile Is Desired

Virtual reality settings include several devices that need to be carried and moved by the users. For instance, virtual reality headsets are most commonly used to provide visual feedback of the virtual world. Input devices, such as wiimotes, smartphones, and tablets, are frequently used to manipulate elements or adjust parameters in the virtual world. These devices allow users to make use of their bodies to explore the virtual environment (e.g., turning the head to look around and rotating the mobile device to rotate a virtual object).

2.4.3.2 Being Eyes-Free Is Desired

When wearing a virtual reality headset, the visual feedback from the real world is no longer available. Users are visually immersed in the virtual world. This can be problematic when users need to get visual feedback from an element of interest in the real world (e.g., locating a button of the input device). Users would then need to remove the virtual reality headset or waste time for locating the button, which disrupts the interaction with the virtual environment. Krum *et al.* [94] proposed the use of plastic panels carved with the shapes of control widgets (e.g., rectangles for sliders, circles for rotary dials). The panels could then be overlaid on top of the mobile device's screen to add passive haptic feedback. This would allow users to discriminate and locate different controls without the need to look at the device. However, this is unpractical in use since the panels would have to be carried around.

2.4.3.3 One-Handed Interaction is Desired

In virtual reality, mobile devices can be effectively used as a 3 degrees of freedom controller [87]. Mobile devices can then alleviate, to some extent, arm fatigue provoked by most multi-degrees-of-freedom input techniques like 3D gestures [87]. Based on this, researchers have introduced techniques for interaction with the virtual world through mobile devices in a one-handed manner. For instance, Handymenu [104] supports one-handed interaction for menu selection and spatial interaction (i.e. selection, manipulation, navigation or parameter adjustment) in virtual environments. Such a interaction technique allow users to perform tasks with minimum arm movements.

2.4.3.4 Sliders are Desired

In virtual environments, users may need to operate controls, such as sliders, to interact with a virtual parameter [94, 103]. Their relevance might be due to its guidance that match the degree of freedom of the virtual task, as in the case of information visualization tasks [1]. In such cases, the use of haptic feedback (like the one provided by touching the flat screen of a smartphone) enables a more efficient interaction

than 2D or 3D virtual controls for docking and pointing tasks [103]. These results have encouraged the use of plastic overlays on top of the mobile device’s surface to provide passive haptic feedback, which is useful for the control of sliders in virtual environments [94]. Further haptic feedback (like the one from tangible interfaces) could also be beneficial in virtual environments.

2.4.4 Summary of Case Scenario

Overall, the aforementioned scenarios present four key aspects: the need of users to be mobile, the need to operate a mobile device without looking at it, the need to operate the mobile device with only one hand, and the need to operate sliders to control a parameter. The lack of support of any of these aspects can greatly affect the performance of the professionals carrying a task. For instance, for audio engineers, using both hands to manipulate a mobile device could prevent them from communication with on-stage musicians. Similarly, for data scientists, not having a graphical user interface on a mobile device would prevent them from physically moving along the wall-size displays while exploring the dataset.

2.5 Conclusion

In this chapter, we have presented the three key topics of our research that are related to interaction with mobile devices, namely eyes-free interaction, one-handed interaction, and sliders.

Eyes-free interaction aims at minimizing the visual attention required by Graphical User Interfaces on mobile devices. Several situations require users to operate their mobile devices in an eyes-free manner. For instance, controlling the sound volume of the speakers at home while walking down the stairs to open the front door, or when crossing a street. Furthermore, the lack of eyes-free interaction can negatively impact the performance time on pointing task, which could be crucial for efficiency demanding jobs.

One-handed interaction refers to the use of only one hand to manipulate mobile

devices. One-handed interaction is widely common on mobile devices. One-handed interaction relies on thumb interaction, as it is the only available finger to interact with the device’s screen. However, due to the anatomy of the hand, the thumb’s range of movement is limited. Such a movement restriction is a problem for one-handed interaction when manipulating most modern mobile devices: users cannot reach all the areas of the device’s screen with the thumb. Hand movements (like handgrip changes and hand relocations) necessary to reach such areas, are uncomfortable and could provoke the fall of the device from the user’s hand.

Sliders are one of the most common widgets for the adjustment of continuous parameters on mobile devices. They are widely used to control parameters of a mobile device (like sound volume, screen brightness) and to control parameters from distant appliances, like a lamp’s light color, speaker’s sound volume. However, sliders’ designs frequently face usability problems. On the one hand, horizontal short-length sliders offer low accuracy due to their small motor scale. On the other hand, vertical long-length sliders suffer from unreachable areas due to the limitations of the thumb’s range of movement.

We then illustrated these three key topics of our research by presenting case scenarios in three different application domains: wall-size displays, virtual reality, and audio engineers. In all the cases, users require carrying a mobile device to interact with a distant appliance. Users require focusing their visual attention on the point of interest of the task that is distant from the mobile device (e.g., on a virtual environment displayed in the virtual reality headset). Users require interacting with the mobile device with a single hand (e.g., using their dominant hand to operate the mobile device while using the non-dominant to communicate with another person). Users require using sliders to control continuous parameters (e.g., performing dynamic queries on plotted data displayed on a large screen).

The following two chapters are related to the design space of this doctoral work. We will review the existing literature on eyes-free one-handed interaction on mobile devices. We will then establish a design space for eyes-free one-handed interaction and present a concept for eyes-free interaction called *Emergeables* (first introduced

in [136]¹) to illustrate how our novel interaction techniques from Part II “Solution Space” could be supported.

¹the author of this thesis was part of the research team

Part I

Design Space

The previous chapter introduces the two main challenges that we address in this doctoral study: eyes-free one-handed interaction with sliders on mobile devices. Our goal is to understand and improve interaction with sliders on mobile devices. To this end, this Part I “Design Space” describes the foundations on which our contributions described in Part II “Solution Space” (made of Chapters 5 and 6) are based.

This Part I is made of two chapters that define the underlying concepts of our contributions: 1) In Chapter 3 we first review the existing literature on eyes-free and one-handed interaction on mobile devices. We focus only on techniques for one-dimensional and two-dimensional pointing tasks and tracking tasks on mobile devices. We characterize the existing techniques for eyes-free one-handed interaction and organize the set of design characteristics into a design space. 2) In Chapter 4 we present a concept called *Emergeables* (introduced in [136]) for eyes-free interaction on mobile devices. Before exploring the design space, we first evaluate the potential of emergeables as a solution for interaction with continuous tangible controls in an eyes-free manner on mobile devices (see Appendix C, page 215). We this chapter we aim at illustrating the mobile device of the future that could support the interaction techniques present in the second part of the manuscript.

Based on the concept of *emergeables* [136] described in Chapter 4, we explore the design space of Chapter 3 in order to define innovative interaction techniques described in Part II “Solution Space”. Figure 2-12 summarizes this adopted research approach that defines the structure of the manuscript.

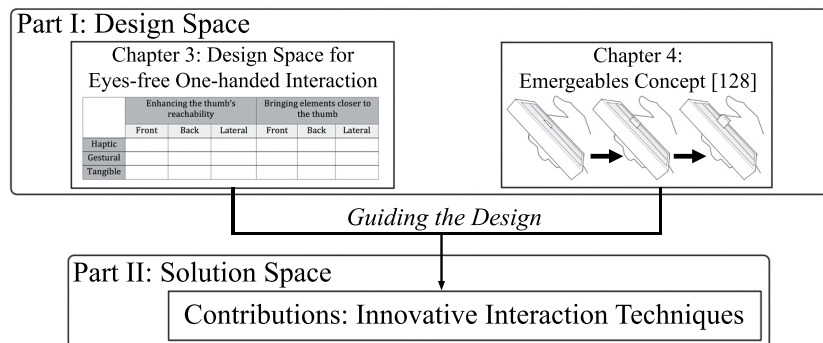


Figure 2-12: Research approach and structure of the manuscript.

Chapter 3

State-of-the-Art Analysis: Eyes-Free and One-Handed Interaction

In this chapter, we present existing techniques related to *eyes-free interaction* and *one-handed interaction* on mobile devices. Since this thesis focuses on the manipulation of sliders on mobile devices in an eyes-free and one-handed manner, we will only review techniques related to pointing and tracking tasks. This type of tasks is common on sliders for the selection of a value within a range of values, for instance, changing the brightness level of the screen a mobile device. Hence, we do not focus on text entry, menu navigation, or shortcuts to access functionalities.

In this chapter, we structure our review of existing techniques as follows:

- First, we present existing techniques that support *eyes-free interaction* on mobile devices. We structure the presentation of these techniques according to:
 - 1) the requirement of the technique for touching the mobile device or not, and
 - 2) the approach used to support eyes-free interaction, for instance on-body or tangible interaction.
- Then, we present existing studies on techniques that facilitate *one-handed interaction* on mobile devices. We structure the presentation of these techniques

according to two identified strategy as well as to the side of the mobile device involved in interaction.

We finally synthesize our review of existing techniques by presenting a design space. The design space is organized along the set of characteristics that we identify for eyes-free one-handed interaction. This design space serves as a first step for researchers to explore new techniques for *eyes-free one-handed interaction* on mobile devices. We will use it for defining new interaction techniques in Part II of this manuscript.

3.1 Mobile Interaction Techniques Supporting Eyes-Free Interaction

Previous studies have focused on eyes-free interaction on mobile devices. Since this doctoral work also focuses on the manipulation of mobile devices with a single hand, and thus touching the mobile device, we categorize the existing techniques according to the *requirement* of the technique to touch the mobile device—i.e., solutions that do not require touching the mobile device, and solutions that do require touching the mobile device.

3.1.1 Solutions that Do Not Require Touching the Mobile Device

Some techniques have focused on interaction without touching the mobile device to support eyes-free interaction. We will present the existing solutions according to the following approaches: *on-body* solutions, like using parts of the body as input surfaces; *wearable* solutions, like smartwatches or garments used as input surfaces; and, *in-air* solutions, like mid-air hand gestures or foot-based gestures.

3.1.1.1 On-Body Solutions

Existing techniques are based on user's body interaction and support eyes-free interaction. These techniques rely on the proprioception (i.e. the sense of the relative position of one's own body parts [64]) to provide feedback to the user. For instance, Serrano *et al.* [145] propose hand-to-face inputs for interaction with head-mounted displays (see Figure 3-1). Authors define hand-to-face inputs as gestures that require contact with the user's face (e.g., touching, rubbing, scratching, caressing). The technique supports sliding, pinching, and cyclic finger gestures as input to perform a task (e.g., panning on a website on a mobile device).

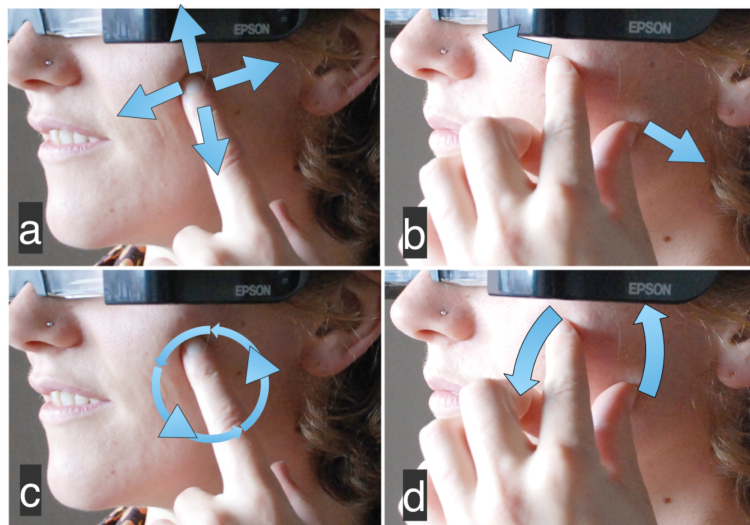


Figure 3-1: Interaction with hand-to-face inputs. Figure from [145].

Mujibiya *et al.* [116] make use of skin interaction through hand gestures to control a distant system. Their underlying technology is based on transdermal low-frequency ultrasound propagation. For this, a receiver is placed on a part of the body (e.g., an arm) and a transmitter is placed on a finger. The receiver captures the ultrasound, sent by the transmitter, which travels through the skin. Users could then perform gestures anywhere on their body to control a distant appliance (e.g., sliding a finger along their arm to lower the sound volume). Similarly, Botential [113] allows users to make use of any part of their body to interact with a mobile device. The technique

relies on a sensor capable of reading the electrical activity coming from the muscles being touched. The system is then able to recognize gestures such as tapping and hovering. Users can then perform a gesture anywhere on their body, like sliding a finger over their belly, to control parameters of the mobile device, like the speakers' sound volume.

3.1.1.2 Wearable Solutions

Existing techniques also support eyes-free interaction with a mobile phone by using additional wearable devices. The following examples depict techniques that require touching a wearable element, for instance, smart watches and garments. These elements are complementary to a mobile device, such as a smartphone, since the actions performed on the wearable element are mapped to actions on the targeted mobile device. For this reason, we consider that these techniques do not require touching the targeted mobile device.

WatchIt [128] is a wrist watch that allows users to extend interaction beyond the watch surface to the wristband. The technique supports 1D gestures (pointing and sliding gestures) to perform pointing tasks on the mobile device. Similarly, Pasquero *et al.* [126] propose the use of a wrist watch to enable eyes-free interaction on mobile devices. The technique relies on gestures (e.g., turn the watch bezel, cover the watch face, and swipe a finger over the watch face) to control parameters of the mobile device.

Pinstripe [86] is a textile interface that allows users to control parameters of a system (e.g., the speaker sound volume of the mobile phone) by performing gestures on the garment. The fabric of the garment is composed of conductive threads that capture the relative displacement of folds in the garment. Users provide inputs in an eyes-free manner by pinching a part of their clothing between two fingers (e.g., thumb and index finger) thus creating a fold in the garment, and then rolling the fold between the fingers (see Figure 3-2). FabriTouch [63] and project Jacquard [132] also make use of conductive fabric on garments to serve as an input surface. The technique allows users to touch the garment, such as dragging a finger, to perform

actions on a mobile device (e.g., controlling the sound volume of the mobile device).

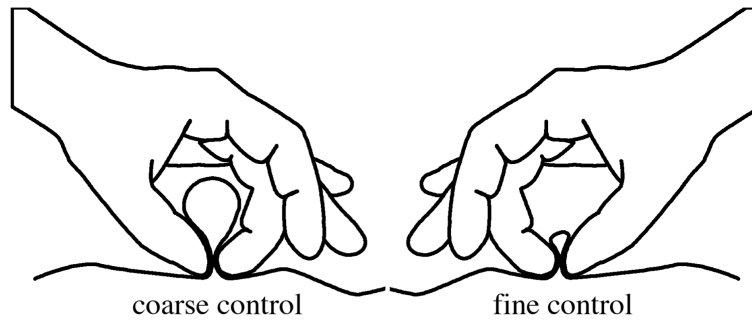


Figure 3-2: Interaction with Pinstripe. Figure from [86].

Elasticcon [92] is a mobile elastic controller that makes use of string-based, elastic interaction to control parameters of a distant appliance. The elastic controller is composed of a retractable string and a set of exchangeable traction knobs. Users can exchange the reference point from which the force is applied to extend the string, from body-centric to ground-based and hand-based (see Figure 3-3). Moreover, users can manipulate the string by pulling, bending, sliding, pinching, or twisting. The aforementioned gestures can be then used as inputs to control a distant system in an eyes-free manner (e.g., selection of a value or zooming a subway map on a head-worn display by pulling a string).

Cheung *et al.* [28] propose the use of an elastic bracelet. The users can deform the bracelet as an input channel in an eyes-free manner. The users can perform different gestures by manipulating the bracelet (like stretching, twisting, rolling, and squeezing), which can be mapped to a continuous range of values and used to interact with a distant appliance, such as a mobile device.

3.1.1.3 In-Air Solutions

Existing techniques based on in-air body gestures (e.g. moving the hand up and down, rotating the foot) support eyes-free interaction on mobile devices. For instance, Dicke & Muller [39] propose the use of in-air gestures with auditory feedback to interact with mobile devices. The technique is based on *imaginary interfaces* [55] in which

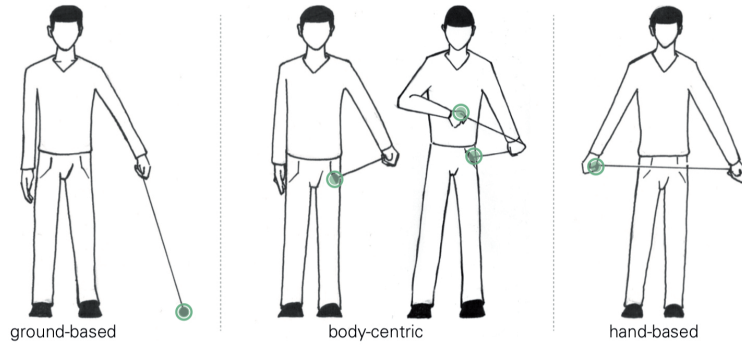


Figure 3-3: Interaction with Elasticcon. Figure from [92].

in-air hand gestures are captured by a wearable camera positioned on the user’s chest. The users perform in-air gestures, like pointing with a finger or pinching, in order to specify actions on the mobile device. For instance, moving vertically the hand while doing a pinch gesture increases/decreases the sound volume of the device (see Figure 3-4).

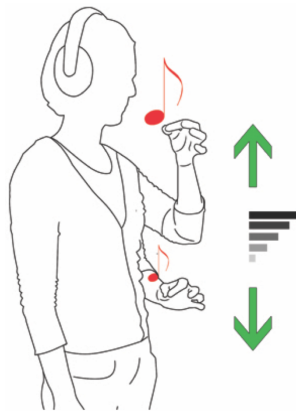


Figure 3-4: Interaction with in-air hand gestures. Figure from [39].

Scott *et al.* [143] have explored foot-based interaction to support eyes-free interaction on mobile devices. The proposed technique makes use of the mobile phone’s accelerometer and machine learning to recognize foot gestures. Coarse foot gestures, such as lifting and rotating, could then be used to interact with the mobile device (e.g., a standing user with both hands engaged could easily control the sound volume

on her mobile phone by rotating her foot).

3.1.1.4 Solutions that Do Not Require Touching the Mobile Device: Summary

The techniques described above aimed at supporting eyes-free interaction on mobile devices. Nevertheless, the proposed techniques present problems.

- On-body and in-air gestures could be mistaken by spontaneous body movements. For instance, a person could scratch her/his face when itching or could move their feet according to the rhythm of a song. Hence, these techniques cannot be active all the time. They require a trigger to activate them and allow the recognition of body or in-air gestures. Moreover, some in-air techniques require audio feedback to inform the user about the system state. This may be inappropriate for situations, such as in social settings or loud environments. Finally some in-air techniques rely on body parts like the feet which might not be available at the desired moment, for instance, when walking.
- Some wearable techniques require extra devices to interact with the mobile device. This might be bothering or uncomfortable to wear or carry around. Other techniques based on intelligent garments might be accidentally triggered by another person or oneself actions. Again such technique may need to be activated before using them.

To avoid these problems, some techniques offer eyes-free interaction with actions on the mobile device only.

3.1.2 Solutions that Require Touching the Mobile Device

Techniques for eyes-free interaction that require actions only with the mobile device are based on the mobile device's sensors. Physical hardware, such as tangible buttons, were the most common type of input since the introduction of mobile devices.

Although modern mobile devices rely mostly on touchscreens as the main input surface, current commercial mobile devices still offer tangible buttons to control different parameters (e.g. volume or screen brightness). However, these type of control mostly afford discrete interaction which can be problematic when selecting a single value in a large range of values. For instance, repeatedly pressing a button for reaching a target is tiring and time-consuming to control a typical volume range (0 to 100), while holding a press on and releasing a button requires high sensorimotor coordination [15].

We now present existing techniques that make use of embedded sensors to support eyes-free interaction according to two categories: *in-air* techniques like tilting and moving the mobile device in mid-air; and *touch-based* techniques like swiping a finger across the device's screen.

3.1.2.1 In-Air Solutions

Making in-air hand gestures while holding the mobile device define one solution for eyes-free interaction. The mobile device becomes an input interaction device like a mouse. Such techniques make use of the embedded accelerometers of the mobile device to capture the movements of the hand. For instance, Boring *et al.* [16] propose gestures like tilting or moving the mobile device in order to control a distant pointer. The users can then move the pointer by moving the mobile device in the air and accelerate the pointer's movement by tilting the mobile device (see Figure 3-5).

Although moving a mobile device in the air could be seen as a specific form of tangible interaction, such an approach does not leverages users from their familiarity with tangible controls –e.g., the sound volume of a speaker are not changed by moving a tangible object up or down in the air. For this reason, we consider in-air techniques different from tangible techniques.

3.1.2.2 Touch-Based Solutions

Existing studies have explored touch-based interaction, such as pinching, swiping, and tapping, to support eyes-free interaction. For instance, Pirhonen *et al.* [131]

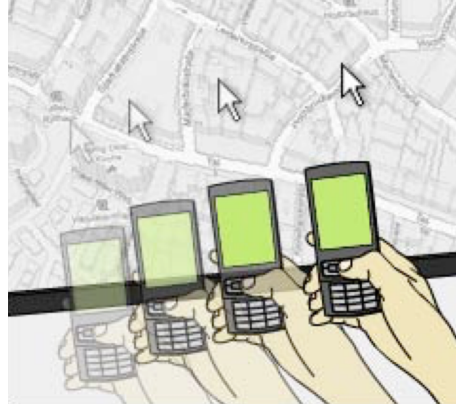


Figure 3-5: Interaction with in-air gestures with the mobile device. Figure from [16].

propose a multimodal system based on gestures performed on the mobile device’s touchscreen and on audio feedback in order to control parameters of a media player in an eyes-free manner. The technique allows users to perform metaphorical gestures to specify actions on the media player. Examples of gestures include swiping up to increase the volume or swiping right to move to the next song. In response to the specified command, audio feedback is provided to the user.

SemFeel [186] proposes the use of vibration patterns to provide haptic feedback to the user when manipulating a mobile device in an eyes-free manner. The technique makes use of five vibration motors located on the borders and at the center of the mobile device. Localized vibrations could then indicate the presence of an item on the touchscreen. The motors’ placement not only allows producing single-point vibrations but also “flows” of vibrations (e.g., vibration moving from left to right). For instance, vibration patterns can provide semantic feedback: a vibration from right to left when the user presses “previous track” on a music player application (see Figure 3-6).

These techniques are based on touch interaction but eyes-free interaction is enabled by audio or haptic feedback. It is worth highlighting that such types of techniques are commonly used to support interaction with mobile devices for visually impaired people (e.g., [8, 82]).

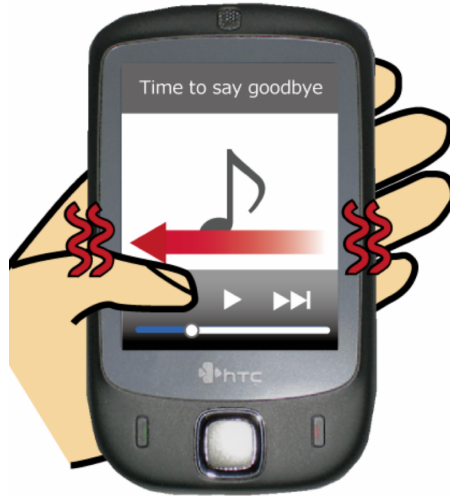


Figure 3-6: Interaction with SemFeel. Figure from [186].

3.1.2.3 Solutions that Require Touching the Mobile Device: Summary

The aforementioned techniques aimed to allow eyes-free interaction in a mobile context. Nevertheless, the proposed solutions require users to learn new interaction techniques. Furthermore, some of these solutions may be inappropriate according to the context of use (e.g., [16]) or loud environments (e.g., [131]). Another approach for eyes-free interaction is the use of tangible interfaces, which leverage users' existing experience with physical controllers.

3.1.3 Tangible User Interfaces

Using physical objects to manipulate digital information was first proposed by Fitzmaurice & Buxton [44], under the term Graspable User Interfaces. Authors reported that the use of multiple specialized physical controls in a space-multiplexing way, i.e., “each function to be controlled has a dedicated transducer, occupying its own space” [44] outperforms time-multiplexing with a conventional mouse. Ullmer & Ishii [78] coined the term *Tangible User Interfaces* for interfaces in which a physical object can be both a representation of the information and a physical control for directly manipulating its underlying association. Tangible user interface became then the widest

spread term to denote physical interaction.

One clear benefit from tangible user interfaces is the fact that a user can interact without the need of looking at the tangible interfaces. Existing studies have evaluated the use of tangible controls adjacent to the screen that displays the object being controlled (e.g., a graphical slider). For instance, Harrison & Hudson [60] studied pneumatic actuated buttons on a stationary interface for eyes-free interaction. The pneumatic actuated buttons result in a relief surface instead of the flat surface of graphical user interfaces. Their results show that the haptic feedback provided by the pneumatic actuated buttons helps the users to focus on a distant point of interest while operating them.

Tory & Kincaid [166] compared the performance and the number of gaze diversions when interacting with tangible, touch, and touch+overlay (i.e. a plastic overlay affixed to a touchscreen) controls. As opposed to Harrison & Hudson's work [60], the authors evaluated continuous controls such as sliders and rotary dials (see Figure 3-7). Their results suggest that the tangible controls require less visual attention than the touch+overlay and touch controls. Also, although authors did not find any performance difference between the tested conditions for sliders, probably due to a problem in their implementation, others studies did show that performance is better with tangible controls [80, 107].

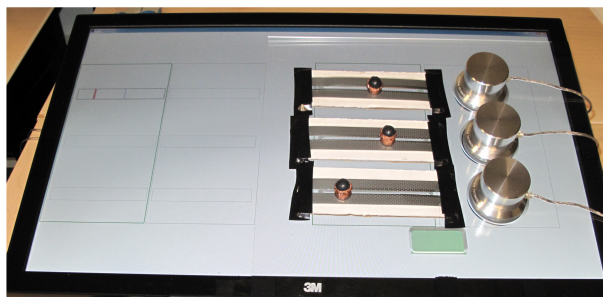


Figure 3-7: Interaction with tangible controls on a tabletop. Figure from [166].

Some studies have also mixed tangible controls with other approaches like dynamic haptic feedback and augmented reality. The goal is to enhance the interaction with

these tangible controls in order to control a distant continuous parameter in an eyes-free manner.

Van Oosterhaut *et al.* [172] tested the influence of haptic force feedback (i.e. movement resistance when operating tangible sliders). The haptic feedback is based on the emotions of the user. A motorized tangible slider varied its movement resistance while users were exposed to pleasant, neutral, and unpleasant visual stimuli. Their results suggest that, for unpleasant stimuli, a counteractive resistance increases the feeling of control. On the contrary, for pleasant stimuli, an assistive resistance (i.e. the motor reduces strength when the user increases speed, reduces the feeling of control). Similarly, Lischke *et al.* [107] studied the influence of variable movement resistance of a tangible slider on performance and mental effort for eyes-free interaction. Authors experimentally compared a motorized tangible slider with a graphical slider. Their results suggest that a tangible slider without haptic feedback (e.g., variable movement resistance) outperforms a graphical slider in terms of movement time while supporting eyes-free interaction. Furthermore haptic feedback on a tangible slider proves to lower the mental effort required by users to perform a pointing task.

Cidrer *et al.* [36] enhanced the functionalities of tangibles sliders through augmented reality. The sliders were enhanced by adding visual information related to the value of the parameter being controlled (e.g., dynamic labeling of the sliders). The sliders were then used to control continuous parameters of a medical application in an eyes-free manner.

Vasquez *et al.* [174] proposed pneumatic tangible controls including sliders, rotary dials and buttons, capable of changing the actuation force to operate them. The controls are composed of 3D printed inflatable chambers. By applying more/less pressure into the chambers, the force required to operate the control is modified (e.g., more pressure into the slider's chambers creates more resistance, thus requiring more force to move the knob). Such device provides dynamic haptic feedback which conveys additional information about the system while the user interacts with the slider in an eyes-free manner. For instance, in a 2D video game context, the slider could move a flying airplane up and down, and the friction could change according

to the turbulence.

Tangible controls have also been studied for interacting with a mobile device. MagGetz [72] makes use of different tangible widgets, such as buttons, sliders, and rotary dials, as an embodied representation of their associated control on the mobile device. The controls are composed of magnets. A magnetic field is captured by a magnetometer embedded in the mobile device. When a control like a slider is moved, the magnetometer records the location change of the control's magnet. Such controls enable the users to adjust parameters of the mobile device like the sound volume of the speaker in an eyes-free manner. However, these controls need to be attached to a stable surface like a table and only work when they are around the targeted mobile device. This hinders the mobility of the user. Similarly, Jansen *et al.* [80] presented portable tangible sliders that could be attached to a mobile device's screen (see Figure 3-8). Authors compared tangible sliders attached to a tablet with graphical sliders displayed on a tablet. Their results show that the tangible sliders outperform the graphical sliders on a pursuit task and are faster to reacquire when the task is interrupted. Moreover, the users glanced at the mobile device 60% more when using graphical sliders, suggesting that the visual attention required by the graphical sliders affects performance.

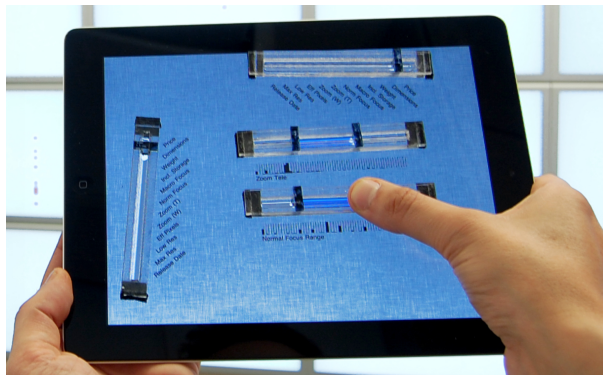


Figure 3-8: Interaction with tangible sliders on a tablet. Figure from [80].

Besides supporting eyes-free interaction, tangible user interfaces also provide other benefits: Tuddenham *et al.* [171] evaluated the manipulation and acquisition of

tangible sliders in comparison with graphical sliders operated with the fingers on a touchscreen and with a mouse. Their results suggest that tangible user interfaces are quicker and easier to acquire. This is probably due to the tangibility of the controls enabling the users to perform well-known grasping gestures. Furthermore, once acquired, tangible user interfaces are significantly easier to manipulate and thus, provide better performance.

3.1.4 Eyes-Free Interaction Techniques: Summary and Design Space

We saw that different approaches have been explored to support eyes-free interaction on mobile devices. We categorize them into two main categories. A first category includes techniques that do not require touching the mobile device. Among these techniques, Botential [113] and similar techniques [145, 116] make use of the user's body as an input surface. The proprioception then plays a key role in providing feedback on the parameter being controlled. However, these techniques are error-prone since the user could touch a part of her/his body (e.g., to scratch it) without wanting to interact with the system. Other solutions (e.g., [128, 126, 86, 63, 92]) make use of wearable devices, such as smartwatches, or garments to interact with the targeted mobile device. However, wearing wrist gear could be uncomfortable for some users, while intelligent garments are prone to accidental interaction in a crowded place, for instance, a public transportation at rush hours. Wearable techniques like the one proposed by Cheung *et al.* [28] require users to use both hands which could be problematic in mobile situations (e.g., users carrying grocery bags). Some in-air techniques like the one proposed by Dickie *et al.* [39] rely on audio feedback, which may be inappropriate for situations, such as in social settings or loud environments. Others in-air techniques use foot movements [143] that might be problematic to perform in mobile situations.

Another category include interaction techniques that require actions with the mobile device. In-air solutions (e.g., [16]) may be inappropriate and impractical in a

	On-Body	Wearable	In-air	Touch-based	Tangible
Techniques that Do Not Require Touching the Mobile Device	Skin as interaction surface [113], [116], [145]	Wristwatch [28], [126], [128] Smart garments [63], [86], [132] Elastic controller [92]	Hand gestures [39] Foot gestures [143]	-	Peripheral controls [72]
Techniques that Require Touching the Mobile Device	-	-	Motion Sensor [16]	Pointing and sliding gestures [131] SemFeel [186]	Attachable controls [80]

Table 3.1: Design space for eyes-free interaction on mobile devices: x-axis - approach used to support eyes-free interaction; y-axis - requirement of the technique regarding touching the mobile device.

limited and crowded place, for instance, a public transportation in rush hours. Other techniques (e.g., [131, 186]) make use of touch-based hand gestures (like swiping and tilting) as an input channel to control parameters in an eyes-free manner. However, these techniques require users to learn new gestures on touch surfaces that do not provide feedback.

Another approach for eyes-free interaction is the use of tangible interfaces, which leverage users’ existing experience with physical controllers. Tangible user interfaces have been extensively used for the control of distant systems in an eyes-free manner [60, 166, 172, 107, 36, 174, 80]. Furthermore, in comparison with common graphical user interfaces, tangible user interfaces are quicker to acquire and easier/more accurate to manipulate once acquired by the user.

We propose a design space (Table 3.1) that is based on the identified properties of our analysis of existing techniques. We aim at helping researchers by providing a framework to guide them in the design of new solutions. The design space is composed of two orthogonal dimensions. The first dimension refers to the requirement from the technique to touch the mobile device or not. Due to this restriction –this is, touching the mobile device– the reviewed literature is not exhaustive regarding eyes-free interaction techniques on mobile devices. The second dimension refers to the

approach used to support eyes-free interaction. The dimension is composed of the five aforementioned conditions for the classification of eyes-free solutions: on-body, wearable, in-air, touch-based, or tangible.

The descriptive power of the design space has been already shown in the previous section (page 46). We positioned existing studies from the literature of eyes-free solutions for mobile devices into the ten cells formed by crossing the two dimensions. Although a mobile device could be worn as wrist watch allowing for wearable and require touching the mobile device, this is impractical due to the size of modern mobile devices.

After having presented the existing works on eyes-free interaction, we review the techniques for one-handed interaction.

3.2 Mobile Interaction Techniques to Facilitate One-Handed Interaction

The users prefer operating their mobile devices with only one hand using the thumb of the hand holding the device. As explained in Section 2.2.1 of Chapter 2.2, areas difficult to reach with the thumb lead to low interaction performance [85] and cause uncomfortable and unstable handgrips [40, 97]. To address this issue and facilitate one-handed interaction several techniques have been proposed.

To structure the presentation of these techniques, we categorize them according to the *strategy used to facilitate one-handed interaction*, and the *side of the mobile device* on which interaction is performed.

Regarding the *strategy used to facilitate one-handed interaction*, we consider the two following strategies:

- Bringing elements close to the thumb's comfortable area: This strategy refers to techniques that focus on displacing the graphical interface through different means (e.g., by tilting the device, by using proxy views, by performing bezel-scroll gestures) in order to bring unreachable areas within the thumb's functional

area;

- Enhancing the thumb’s reach capabilities: This strategy refers to techniques that make use of graphical widgets (e.g., magnetic sticks) or of another modality (e.g., operation with the index finger on the back side of the mobile device) that serve as an extension of the thumb to reach elements outside the thumb’s functional area.

Regarding the *side of the mobile device*, we used the most common surfaces for interaction considering a portrait stance of the device:

- Front: The front side of a mobile device is the main surface of interaction, usually composed of a touchscreen and sometimes of a physical keyboard. The thumb is commonly used to interact with the front side since most users prefer operating the mobile device with a single hand [85]. This motivated the studies that model the thumb’s functional area on the front side of the mobile device [12] and then explore solutions according to the thumb’s reach.
- Back: Most mobile devices present a flat non-interactive back side. However, manufactures have started to use this back side of the device for interaction (e.g., unlocking the mobile device through finger recognition with sensors on the back of the device). Moreover, several studies have shown the benefit of using Back-of-Device interaction for targets outside the thumb’s range of movement. Wobbrock *et al.* [179] showed the benefits of Back-of-Device interaction for one-handed mobile interaction. Authors suggest using the index finger for Back-of-Device interaction. Moreover, the index finger presents the larger functional area on the back of mobile devices [98]. Such a handgrip, in which the index finger covers the upper half back side of the mobile device, is a commonly observed single-handed grip [40, 57].
- Lateral: Current mobile devices include physical buttons at either lateral sides of the device, which are commonly used to control parameters such as volume, brightness and locking the device. For the sake of understanding, we will refer

to “lateral side” as the lateral side reachable with the remaining fingers of the hand. This is a commonly adopted approach for side-of-device interaction [69, 79, 153], since it also supports interaction on the front side with the thumb. Thus, we will not consider the lateral side that is close to the thumb.

In the following sections we successively consider the two strategies. For each strategy we review the existing techniques according to the side of the device on which interaction takes place.

3.2.1 Bringing Targets Closer

3.2.1.1 Interaction on the Front Side

Existing techniques, based on Front-of-Device interaction, focus on displacing the elements of the graphical interface closer to the thumb’s functional area. Currently, some manufacturers have added functionalities to their mobile devices to facilitate one-hand interaction (e.g., double-tapping the home button on iOS will bring the top half of the screen down to the middle of the display).

Chang *et al.* [25] make use of tilting gestures of the mobile device in order to fit the interface within the comfortable area of the thumb. The authors propose three mobile interaction techniques: TiltSlide, in which the system slides the screen in the tilting direction; TiltReduction, in which the system shrinks the screen when a tilting gesture is performed; and TiltCursor, a cursor that appears and moves in the tilting direction, helping the thumb to reach far-located elements. This last technique, namely TiltCursor, does not move graphical elements within the comfortable area of the thumb but extends the reachability of the thumb. Presented here as part of three techniques based on tilting gestures, this technique belongs to the second strategy presented in Section 3.2.2.

MovingScreen [169] provides a movable screen view of the whole interface. The movable aspect allows the users to position a part of the graphical interface within the comfortable area of the thumb in order to select the intended target. The movement of the screen view is triggered by a vertical bezel swipe gesture. The length of the

gesture implicitly determines the thumb’s comfort zone and sets the moving speed of the screen view. Kim *et al.* [90] proposed a movable screen that works in a similar way to MovingScreen [169] but using a long touch as a trigger.

ThumbSpace [84] offers a proxy view of a sub-region of the interface in order to facilitate the interaction with out-of-reach targets within the comfortable area of the thumb. Such an approach has been also applied on large mobile devices, such as tablets, in order to bring targets closer to the thumb’s reach [180]. Yu *et al.* [188] present two techniques. First, CornerSpace is triggered by a bezel swipe gesture and allows easy access to targets near any of the four corners of the screen. It makes use of a circular widget with four buttons representing the four corners. Second, BezelSpace makes use of a “magnetized” cursor that moves accordingly to the thumb’s movement. The “magnetized” feature attracts the cursor to the nearest target when it is closer than a predefined threshold. The technique is triggered by keeping pressed down any of the corners of the “magnetized” cursor. This activates a mapping between the user’s thumb and an invisible proxy region similar to the one of ThumbSpace. The difference is that the proxy region adaptively shifts according to the location of the “magnetized” cursor.

3.2.1.2 Interaction on the Back Side

Based on Back-of-Device interaction, Le *et al.* [97] adopted a similar approach that consists of displacing the graphical elements. The Back-of-Device technique enables the users to drag the graphical interface displayed on the front side with the index finger on the back side in order to bring out-of-range targets within the thumb’s range of movement on the front side. In a recent study, Le *et al.* [99] extended this approach by using machine learning to recognize the fingers on the back side of the mobile device. The dragging of the graphical interface displayed on the front side could then be initiated by a particular finger on the back side.

3.2.1.3 Interaction on the Lateral Side

Studies have explored the use of the lateral sides of the mobile phones to facilitate one-handed interaction [69, 79, 153]. Unifone [69] makes use of pressure sensors placed on one of the lateral sides of a mobile phone. By exerting pressure along the lateral side, users can then control different applications' functionalities, such as browsing, map navigation and text formatting.

Jang *et al.* [79] proposed the use of actuated pins on a lateral side of a mobile phone as both inputs and outputs. As outputs, the array of pins rely on the physical affordance given by the actuated pins (i.e. when a vertical slider is displayed on the screen) pins would pop out at the same height as the graphical slider's knob. As inputs, the pins can be manipulated to serve as several widgets (e.g., buttons, sliders, and toggle switches). Similarly, ShiftIO [153] makes use of tangible elements on the lateral side of a mobile phone for inputs and outputs. The tangible elements move around the mobile phone's edges through electro-magnets embedded in the device.

Although none of these techniques have been used to bring targets closer to the thumb's comfortable area, they define a solution to trigger the displacement of graphical elements displayed on the front side. For instance, the actuated pins [79] and ShiftIO [153] could be used to displace the screen's interface up or down. Similarly, Unifone [69] could map the pressure exerted on the lateral pressure sensor to displace graphical elements in order to bring targets closer to the thumb.

3.2.1.4 Bringing Targets Closer: Summary

The studies described above aimed at facilitating one-handed interaction on mobile devices by displacing the graphical elements of the interface closer to the thumb's functional area. All the presented techniques imply a first task to displace the interface, followed by the main task. For instance, double-tapping the home button (first task) on iOS will bring the top half of the screen down to the middle of the display to access out-of-reach targets (main task). This additional first task is performed by interacting with the front, back or lateral sides of the device.

One drawback of this strategy is that the users are required to perform an additional task before performing the main task: this could lead to a loss in interaction performance for situations that require efficiency in the operation of the device (e.g., audio engineers usually working under tight time schedules). Avoiding this two-step process another strategy is to enhance the reachability of the thumb.

3.2.2 Enhancing the Thumb’s Reachability

3.2.2.1 Interaction on the Front Side

Instead of moving targets, existing techniques enhance the thumb’s reachability. Based on Front-of-Device interaction, Roudaut *et al.* [138] presented MagStick, a technique that uses a telescopic stick with a “magnetized” cursor. The cursor appears at the touched position and moves in the opposite direction of the thumb’s movement. Such an approach has been also applied on large mobile devices, such as tablets, in order to facilitate the access to hard-to-reach targets [180]. 2D-Dragger [158] is a touch-based technique that skips the empty space between selectable targets. This reduces the motor distance between the thumb and the intended target. When dragging the thumb towards a target, visual feedback is provided when a target is available for selection.

3.2.2.2 Interaction on the Back Side

Existing techniques, based on Back-of-Device interaction, enhance the thumb’s reachability by using the back side as a modifier of the main modality on the front side. BackPat [144] facilitates multi-target selection in a list with Back-of-Device interaction. Users can select several targets from a list on the front side with their thumbs. When targets are outside the thumb’s functional area, users can tap on the back side to extend the targets’ selection. This allows users to select out-of-reach targets. HybridTouch [159] and Dual-Surface [184] consider the front side as an absolute pointing area while the backside behaves as a track pad for relative movements. When the thumb cannot reach a target, users are able to do clutching movements with a finger

on the back of the device to reach the target.

3.2.2.3 Interaction on the Lateral Side

The techniques presented in the subsection 3.2.1.3 could also be used to enhance the thumb’s reachability. For instance, for the control of sliders, Unifone [69] could control the slider’s knob in a rate-control manner through pressure, while the thumb could operate the knob in a position-control manner. For the techniques in [79, 153], the tangible elements on the lateral side could serve as the slider’s knob. The users could then operate the lateral knob to reach targets outside the thumb’s comfortable area. But the aforementioned techniques were not designed for enhancing the thumb’s reachability and therefore have not been experimentally tested in this context.

3.2.2.4 Enhancing the Thumb’s Reachability: Summary

The studies described above aimed at facilitating one-handed interaction on mobile devices by enhancing the thumb’s reachability. The two main advantages of this strategy in comparison with the previous one are (1) that the whole interface is always visible and available at any moment and (2) that the technique does not imply an additional task to move the graphical elements. Nevertheless, one key drawback is that the users are required to learn how to use uncommon techniques (e.g., operating magnetized cursors [138], or using the back side of the device to point at targets in a relative manner [159, 184]). This defines a steeper learning curve, which can ultimately affect the user’s performance [32] and more importantly can compromise its wide adoption.

3.2.3 One-Handed Interaction: Summary and Design Space

We presented different techniques to facilitate one-handed interaction on mobile devices. We categorized them into two main categories: 1) bringing elements close to the thumb’s comfortable area, and 2) enhancing the thumb’s reach capabilities. For each category we consider the sides of the mobile device on which interaction takes

place. This structured analysis lead us to define a design space composed of two dimensions and presented by Table 3.2. The first dimension (x-axis) refers to the two identified strategies and the second dimension (y-axis) the side of the mobile device on which interaction takes place. The descriptive power of the design space has been already shown in the above section, in which we positioned existing techniques from the literature of mobile one-interaction into the six categories formed by crossing the two dimensions. We did not consider Chang’s work [25] in the design space since their technique requires tilting the mobile phones. Indeed tilting could lead to an handgrip change and our review of exiting techniques focuses on thumb’s interaction without any handgrip change. We also did not position the techniques based on interaction on the lateral sides [69, 79, 153] since their design did not initially focus on facilitating one-handed interaction.

	Bringing Elements Closer to the Thumb	Enhancing the Thumb's Reachability
Front Side of the Mobile Device	ThumbSpace [84] Repositioning the interface [90] MovingScreen [169] CornerSpace/BezelSwipe [188]	MagStick [138] 2D-Dragger [158]
Back Side of the Mobile Device	Repositioning the interface [97]	BackPat [144] HybridTouch [159] Dual-Surface [184]
Lateral Side of the Mobile Device	-	-

Table 3.2: Design space for one-handed interaction on mobile devices: x-axis - strategy used to facilitate one-handed interaction; y-axis - side of the device on which the technique is performed.

In the following section we will enrich this design space for one-handed interaction with the dimensions for eyes-free interaction identified in Section 3.1 in order to provide a design space for eyes-free one-handed interaction techniques.

3.3 Design Space for Eyes-Free One-Handed Interaction

We propose a design space (Table 3.3) that presents key characteristics for the design of eyes-free one-handed interaction techniques. We aim at helping researchers by providing a framework with which they could guide themselves for the design of new techniques. Furthermore, we will use this design space to position our contributions (Chapters 5 and 6) in comparison with existing solutions for eyes-free one-handed interaction.

The design space is composed of three orthogonal dimensions from the previously described design spaces for eyes-free interaction and one-handed interaction. We briefly recall each dimension.

The first dimension refers to the *strategy used to facilitate one-handed interaction*. This dimension includes two strategies:

- **Bringing elements close to the thumb’s comfortable area:** This strategy refers to techniques that focus on displacing graphical elements in order to bring unreachable areas within the thumb’s functional area;
- **Enhancing the thumb’s reach capabilities:** This strategy refers to techniques that make use of graphical widgets (e.g., magnetic sticks) or of another modality (e.g., operation with the index finger) that serve as an extension of the thumb to reach elements outside the thumb’s functional area.

The second dimension refers to the *approach used to support eyes-free interaction*. For this dimension, we do not consider the approaches presented in Section 3.1.1 (page 46) that do not require touching the mobile device. In this thesis, we focus on eyes-free techniques that can be performed with the same hand that holds the mobile device. The reason for this is to: 1) allow users to keep a free hand to serve other purposes. For instance, carrying a grocery bag and, in the audio engineers case, to hold a microphone to communicate with musicians on stage; and 2) avoid users stop using their mobile device in order to perform an eyes-free technique that does not

require touching the device. This is important for audio engineers as they desire tools that allow them to have a good performance due to tight time schedules. For these reasons, we consider three values corresponding to the case of techniques that require touching the mobile device as described in Section 3.1.2:

- **Touch-based:** this approach makes use of hand gestures, such as tapping, swiping, and tilting, to interact with mobile devices in an eyes-free manner.
- **In-air:** this approach relies on in-air body gestures (e.g., moving the hand up and down, rotating the foot) to support eyes-free interaction.
- **Tangible:** this approach presents tangible elements on the surface of the mobile device to support eyes-free interaction.

The third dimension refers to the *side of the mobile device* (see Section 3.2) on which interaction takes place. It is composed of the three main sides used to interact with a mobile device:

- **Front:** the front side of the mobile device composed of a touchscreen and sometimes of a physical keyboard;
- **Back:** the back side of the mobile device on which interaction with the index finger can take place;
- **Lateral:** the lateral sides of the mobile device reachable by other fingers than the thumb in the context of one-handed interaction.

By combining the two design spaces and therefore the two points of view, namely eyes-free and one-handed interaction, we discarded some techniques:

1. Regarding eyes-free solutions, we do not include touch-based techniques like SemFeel [186] and Pirhonen *et al.*'s work [131] (page 52) that rely on gestures, such as tapping or swiping, because they do not solve the problem of unreachable targets. The in-air solution presented in [16] (page 52) aimed at interaction with a distant appliance, by ray-casting a pointer on the targeted appliance, and not with the device itself.

- Regarding one-handed solutions, we do not include the techniques based on the front and back sides of the mobile device since they rely on graphical interfaces and thus, preventing users from being eyes-free. Some techniques (e.g., [79, 153], page 64) based on the lateral side of the device are tangible and therefore support eyes-free interaction. However, these techniques were not designed to facilitate one-handed interaction. Thus, as in Section 3.2.3, we will not position these works into the proposed design space.

The presented design space (see Table 3.3) is elaborated from well-established design characteristics for eyes-free and one-handed interaction with mobile devices. We could not find a technique from the existing literature that fits into our design space. This is due to the fact that existing solutions tackle either eyes-free or one-handed interaction but not both. We expect that our design space serves as a first step for researchers to explore new techniques for eyes-free one-handed interaction on mobile devices. Later in this doctoral work (see Solution Space, page 80), we will present new interaction techniques based on this design space.

	Bringing Elements Closer to the Thumb			Enhancing the Thumb's Reachability		
	Front	Back	Lateral	Front	Back	Lateral
In-air	-	-	-	-	-	-
Touch-based	-	-	-	-	-	-
Tangible	-	-	-	-	-	-

Table 3.3: Design space for eyes-free one-handed interaction on mobile devices: x-axis - strategy used to facilitate one-handed interaction, which could be performed on different sides of the device; y-axis - approach used to support eyes-free interaction; z-axis - side of the mobile device on which the technique is performed.

3.4 Conclusion

In this chapter, we have introduced the state-of-the-art regarding eyes-free one-handed interaction solutions. The existing solutions aim to provide eyes-free interaction when

needed (e.g., in social settings or when crossing a street) and to avoid uncomfortable and unstable handgrips when using the mobile device with only one hand.

From the reviewed literature, we organized the set of design characteristics into a design space for eyes-free one-handed interaction. The design space allows the characterization of the existing techniques for eyes-free one-handed interaction. The design space is composed of three orthogonal axes:

- The first dimension refers to the *strategy used to facilitate one-handed interaction*.
- The second dimension refers to the *approach used to support eyes-free interaction*.
- The third dimension refers to the *side of the mobile device* (see Section 3.2) on which the technique is performed.

The presented state-of-the-art shows that tangible user interfaces do not only support eyes-free interaction but also provide clear benefits in comparison with graphical user interfaces. For instance, tangible controls are quicker to acquire and easier and more accurate to manipulate once acquired. Focusing on tangible interaction for eyes-free interaction, the following chapter presents a concept for eyes-free interaction called *Emergeables* (first introduced in [136]¹). The concept relies on shape-changing mobile devices capable of protruding tangible controls out of their surfaces. The concept of *emergeables* open new possibilities in the design space of Table 3.3 for the line Tangible that we present in Part II Solution Space (Chapters 5 and 6).

¹the author of this thesis was part of the research team

Chapter 4

State-of-the-Art Analysis: Emergeables, Dynamic Tangible Controls on Shape-Changing Mobile Devices

There are several case scenarios where having tangible controls on mobile devices is desired (see Section 2.4, page 33). For instance, audio engineers need to be mobile in order to find weak sound spots around the venue and adjusting audio parameters to correct such spots (see Section 2.4.1, page 33). At the same time, they need to keep visual contact on the stage in order to receive cues from the performers. One way to solve such problems is through shape-changing mobile devices that can offer tangible controls, such as rotary dials and sliders, anywhere on their display surface.

Several benefits of tangible interaction have been defined, e.g., ease of manipulation, reduced need for visual attention (see Section 3.1.3, page 54). These advantages are also noticeable in dynamic situations when, for instance, people still prefer to swap between multiple physical controls [14]. In our design space for eyes-free interaction (section 3.1), tangible interaction is one type of possible interaction (one column in the design space). A prior study (described in Section 3.1.3 and classified in our

design space for eyes-free interaction as tangible interaction that requires touching the mobile device) has shown the benefits of reconfigurable tangible controls via detachable sliders that could be used with a mobile touchscreen surface [81]. However, carrying a collection of tangible elements is clearly impractical in reality. For such situations, mobile deformable displays that protrude physical widgets could allow the device to take the shape of the most appropriate control for the situation at hand while supporting the benefits of tangible interaction.

On-demand rendering of physical controls has previously been proven beneficial for static buttons (see Section 3.1.3). Nevertheless, there is a significant gap around tangibility of *continuous* controls, like sliders and rotary dials, for mobile situations. This is important since continuous controls, like sliders, are widely used on mobile devices (see Section 2.3, page 27).

In this chapter, we present *Emergeables* – a demonstration of how tangible controls could be dynamically created on shape-changing mobile devices. The concept (first introduced in [136]) envision a mobile device in which any control widget can appear on its surface (see Figure 4-1) – affording the flexibility of a graphical interface, and the affordance and tactile benefits of tangibles.

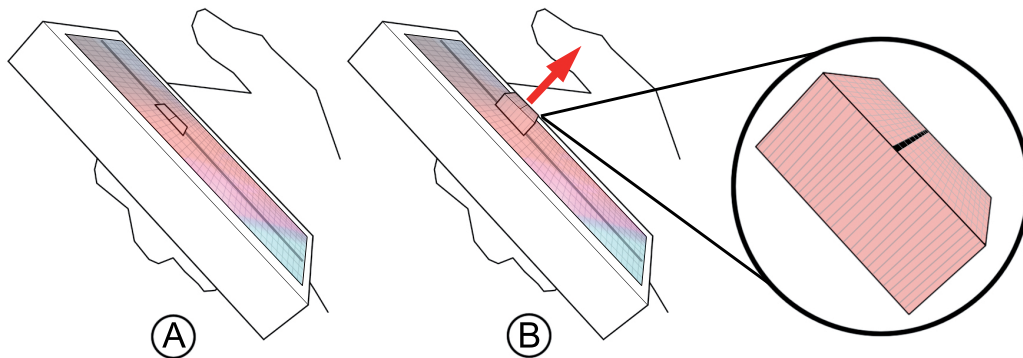


Figure 4-1: Envisioning an emergeables device: (A) A slider is graphically presented on the surface of the device; (B) sensors – composed of several physical pixels capable to raise and fall – start to morph out (direction of the red arrow) from the screen’s surface to render a tangible slider’s knob ready to be used.

4.1 Emergeables Concept

While display-screens are constructed of pixels, emergeables' elementary unit is a *sensel* – a cluster of physical pixels capable to raise and fall anywhere on the display surface – with two key properties:

- **Manipulation:** Sensels can be manipulated by the user. We analyze two basic manipulations from [23]: translation and rotation.
- **Size/Resolution:** The size of each sensel establishes the resolution of the emergeable interface. The size of each sensel is independent of the pixel resolution of the *display* surface.

Our ultimate goal is to create very high-resolutions emergeables, on the order of millions of sensels. This would allow users to grab and manipulate groups of sensels to interact with, for instance:

- A dial, by rotating sensels around the Z-axis;
- A mouse wheel, by rotating sensels around the X-axis;
- A slider, by translating the sensels in the Y-axis (see Figure 4-2).

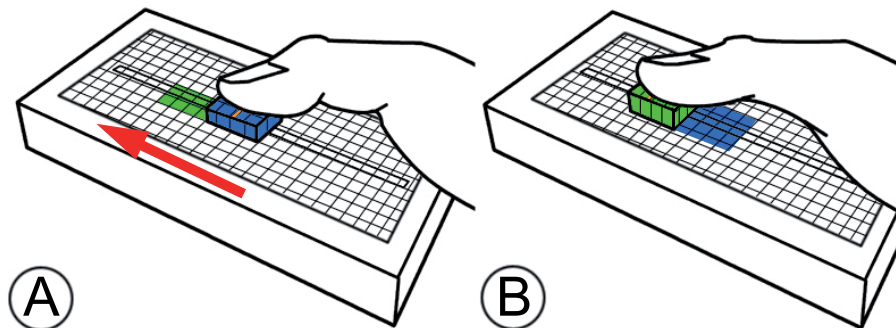


Figure 4-2: Operating a rendered tangible slider on an emergeables device: (A) A rendered tangible slider knob (in blue) is about to be displaced (direction of red arrow). New pixels (in green) will emerge to render the new location of the knob. (B) The unused pixels (in blue) go back to the flat surface of the screen.

Beyond *manipulation* and *resolution*, there are other tangible characteristics that could be explored. For instance, as explained in [3], controls could physically change to make crucial actions more difficult to perform. Furthermore, tangible controls could also change their *textures* (e.g., [77]) and *response* (e.g., some moving smoothly, others with more resistance [175]). These features will certainly generate a broad range of interaction experiences with a prototype, including a method for eyes-free recognition of controls as they emerge. In this chapter, we focus on the two key ones that describe the fundamental operation of the controls, namely *manipulation* and *size/resolution*.

In order to demonstrate and test the potential of *Emergeables*, two emergeable prototypes were built: 1) a high-resolution prototype, where controls appear on the surface in a set of fixed positions; and 2) a low-resolution prototype that uses a rod-based widget model to render lower-resolution controls, which provide flexibility in positioning. In a controlled experiment (see Appendix C, page 215) these prototypes were tested in order to evaluate the impact that the *Emergeables* concept has on the performance and on the required visual attention when manipulating continuous controls (i.e. dials and sliders) in comparison with a graphical user interface.

4.1.1 Case Scenario

Emergeables depart from existing shape-changing research by endeavouring to provide truly direct interaction with affordances, controls and content integrated within a visual display. Our ultimate long-term aim is to create a mobile device where any control widget can appear anywhere on its surface. We present the following scenario to illustrate the approach:

Alex is playing a role-playing game on his Xbox and is keen to use his new Emergeable mobile to enhance the experience. While focused on his television screen, Alex pulls out his mobile, which begins acting as a controller. At the start of a mission, his character needs to drive a car, so the controls on his touchscreen become a steering wheel, joystick gear lever and raised gas and brake pedals. When he arrives at his destination, there's a lock to pick, so the controls morph into two levers he has to gently manipulate to tease out the pins of the bolt. After opening the door, he notices

some items on the table. His mobile shifts to reveal 3D representations of the objects so he can select which ones he wants to pick up by touch alone. As he moves towards the next room he hears voices: the touch-screen quickly changes shape to reveal the weapons Alex has in his possession, and he quietly arms himself ready for combat.

4.2 Summary

In this chapter we have presented the concept of *Emergeables* (first introduced in [136]¹) for the eyes-free control of continuous widgets. The concept focuses on facilitating interaction with continuous controls on mobile devices for situations where eyes-free interaction is required, e.g., using sliders to operate distant appliances (see Section 2.4, page 33).

In a controlled experiment (see Appendix C, page 215), two prototypes were built to test the viability of tangible, continuous controls that ‘morph-out’ of a flat screen. The obtained results show the potential and benefits of emergeable, high-resolution, tangible controls in terms of accuracy, visual attention and user preference. This is important since continuous controls, such as sliders, are widely used on mobile devices (see Section 2.3, page 27). Furthermore, eyes-free interaction is a desired feature when interacting with mobile devices (see Section 2.1, page 10).

The concept of *Emergeables* [136] contributes to the design space for the manipulation of mobile devices in an eyes-free manner (see Section 3.1, page 46). In Table 4.2 we position *Emergeables* in the design space.

The foundational aspect of *Emergeables* [136] for our work motivated us to present the concept in Part I Design Space. Moreover, *Emergeables* define a concept that combined with our design space of the previous chapter (page 68) is foundational for our contributions presented in Part II Solution Space (page 80). Indeed, the *Emergeables* concept opens new research avenues, such as one-handed interaction with shape-changing continuous widgets on mobile devices, that we address in the remaining chapters of this thesis.

¹the author of this thesis was part of the research team

	On-Body	Wearable	In-air	Touch-based	Tangible
Techniques that Do Not Require Touching the Mobile Device	Skin as interaction surface [113], [116], [145]	Wristwatch [28], [126], [128] Smart garments [63], [86], [132] Elastic controller [92]	Hand gestures [39] Foot gestures [143]	-	Peripheral controls [72]
Techniques that Require Touching the Mobile Device	-	-	Motion Sensor [16]	Pointing and sliding gestures [131] SemFeel [186]	Attachable controls [80] Emergeables [136]

Table 4.1: The *Emergeables* concept positioned in the design space for eyes-free interaction on mobile devices of section 3.1: Tangible interaction (x-axis); Touching the mobile device is required (y-axis).

The following contributions will present interaction techniques for eyes-free one-handed interaction based on the *Emergeables* concept [136]. Furthermore, we will use the design space introduced in Section 3.3 (page 68) to guide the design of the interaction techniques. We will focus on sliders since they are commonly used for distant tasks with mobile devices (see Section 2.4, page 62). Moreover, we will consider interaction on the front and back sides of a mobile device since the functional area of the fingers involved in Front- and Back-of-Device interaction is already known (see Sections 2.2.2.2.1 and 3.2). On the contrary, there is no knowledge of the functional area of the fingers involved when interacting on the lateral sides of a mobile device.

Part II

Solution Space

In Part I Design Space (page 43) the foundations for the design of mobile eyes-free one-handed interaction techniques were defined. For this, we established a design space for eyes-free one-handed interaction on mobile devices based on characteristics from existing techniques (see Section 3.3, page 68).

We then define three new interaction techniques for eyes-free one-handed interaction with sliders on mobile devices based on the concept of *Emergeables* [136] presented in Chapter 4. Also, the techniques were designed according to the set of design characteristics presented in the design space from section 3.3 (see Figure 4-3)

This Part II is made of two chapters that explore the three new interaction techniques: 1) In Chapter 5 we explore two interaction techniques based on front side interaction on mobile devices. The first technique aims at facilitating one-handed interaction by changing the orientation and length of the slider. The second technique relies on thumb-clutching movements on an extendable tangible slider to support eyes-free one-handed interaction. 2) In Chapter 6 we explore back side interaction on mobile devices with a technique that involves Front- to Back-of-Device interaction with a shape-changing tangible slider.

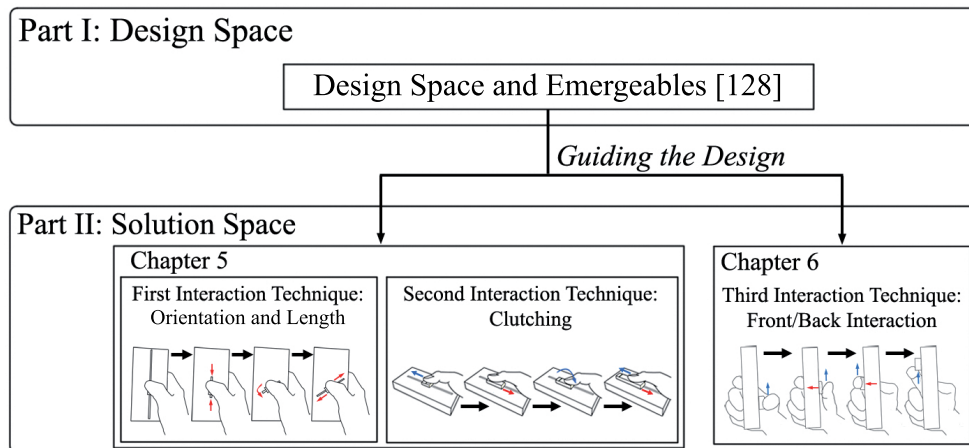


Figure 4-3: Three new interaction techniques were designed according to the design space on eyes-free one-handed interaction (section 3.3) and the *emergeables* concept (Chapter 4).

Chapter 5

Front Side Interaction

The current trend of touchscreens has turned the front side of mobile devices into the main input surface. When using only one hand to operate mobile devices, the thumb is the most common finger used to interact with the front side of the device. However, the thumb has a limited range of movement due to anatomical constraints (see Section 2.2.2.2, page 21) that prevent users from reaching all the input surface of the mobile device.

In Section 3.2 (page 60), we reviewed the existing solutions for one-handed interaction on the front side of the mobile device. The techniques aim to keep interaction inside the functional area of the thumb, i.e., the area the thumb can easily reach, as described in Section 2.2.2.2 (page 21). Nevertheless, techniques from the literature do not support eyes-free interaction. In this chapter, we present two new interaction techniques for eyes-free one-handed interaction on mobile devices.

The techniques are based on the *emergeables* concept [136] described in the previous chapter (page 73). We rely on shape-changing tangible widgets to support eyes-free interaction and facilitate the manipulation of sliders in a one-handed manner. In this context, two approaches, as described in Section 3.3 (page 68), are possible: bringing elements closer to the thumb's functional area, and enhancing the thumb's reachability. We then focus on addressing the following research question: for facilitating one-handed interaction on the front side of mobile devices, is it better to fit the slider within the functional area of the thumb (Section 5.1), or to use large

sliders and enhance the reaching capabilities of the thumb through clutching (Section 5.3)?

5.1 Bringing Elements Closer to the Thumb's Functional Area

One solution to acquire targets far from the thumb's reach consist of displacing the whole interface to move targets closer to thumb's functional area. Several research studies (described in Section 3.2.1, page 62) have proposed different interaction techniques to facilitate the displacement of the interface on mobile devices. For instance, by tilting the mobile device [25] or performing a bezel-swipe gesture to trigger the displacement [169]. Some manufacturers have added functionalities to their mobile devices to bring targets closer to the thumb's functional area (e.g., double-tapping the home button on iOS will bring the top half of the screen down to the middle of the screen). However, the aforementioned techniques rely on graphical user interfaces which require the user's visual attention as described in Chapter 4. We focus on facilitating one-handed interaction while supporting eyes-free interaction.

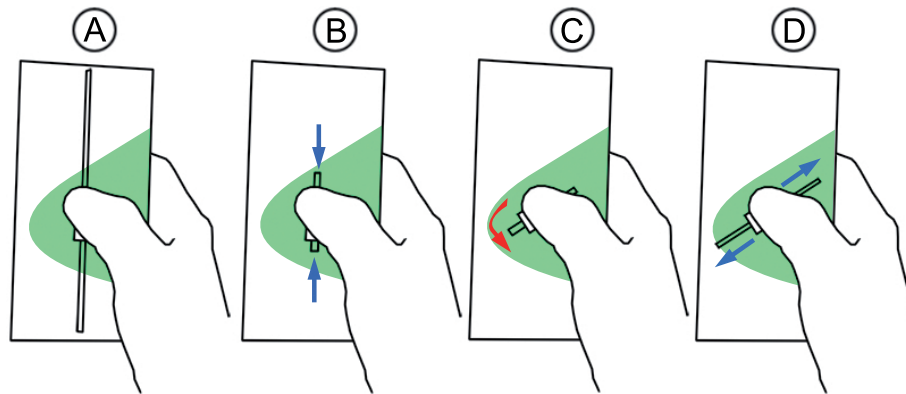


Figure 5-1: (A) A shape-changing tangible slider. (B) The slider can shrink/expand (blue arrows) to fit within the comfortable area of the thumb (green area) when used in a one-handed manner. (C) The slider can also change its orientation (red arrow) in order to facilitate the thumb's movements. (D) The tilted slider expands within the thumb's comfortable area in order to support a larger motor scale.

Based on the above approach that we apply to shape-changing tangible controls for eyes-free interaction, we study a tangible slider that varies in orientation and length in order to be manipulated by the thumb within its functional area. The tangible slider can expand/shrink itself to fit within the thumb’s comfortable area (see Figure 5-1, A-B) and change its orientation from vertical to tilted (see Figure 5-1, C-D) in order to facilitate the thumb’s movement [85]. Moreover, the tangible aspect of the slider allows operation without looking at the device. In Table 5.1, this technique, namely a tangible slider capable of changing its orientation and length, is positioned in our design space of Chapter 3.

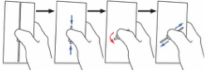
	Bringing elements closer to the thumb			Enhancing the thumb’s reachability		
	Front	Back	Lateral	Front	Back	Lateral
In-air						
Touch-based						
Tangible	 <p>Changing the orientation and length of tangible sliders</p>					

Table 5.1: The shape-changing tangible slider positioned in the design space for eyes-free one-handed interaction on mobile devices: Bringing elements closer to the thumb (x-axis); (y-axis); Front side (z-axis).

As explained in Section 2.2.2.3 (page 25), handgrip changes are required to reach targets outside the thumb’s functional area. Hand relocations are required when handgrip changes are not sufficient for reaching the target. With this technique, we focus on avoiding handgrip changes, and thus avoiding hand relocations.

We experimentally explore our solution. The two main contributions of this experimental study are:

1. The identification of the impact of the properties (orientation and length) of a tangible slider on performance when they are operated with the thumb of the hand that holds the mobile device.
2. The definition of an area outside the functional area of the thumb which re-

quires handgrip changes to reach targets. Such area is intermediate between the functional area of the thumb and the hand relocation area.

In the following section, we describe the performed experiment to evaluate tangible sliders with different orientations and lengths. We conclude this experimental study by discussing the impact of the properties of tangible sliders on eyes-free interaction and one-handed interaction.

5.2 Experiment: Impact of the Slider’s Orientation and Length on Performance

To inform the design of shape-changing tangible sliders on mobile device, we conducted an experiment to evaluate the impact of orientation and length of a tangible slider on pointing performance and grip. The experiment followed a within-subject design with two independent variables:

- **Orientation:** vertical, tilted;
- **Length:** small, long.

The *Orientation* variable is composed of two states: vertical (90 degrees) and tilted (68.1 degrees). We choose a vertical orientation since it is a common slider orientation on appliances (see Section 2.3.2, page 30). For the tilted condition, we use an angle of 68.1 degrees, which is the maximum radial angle of the thumb (as explained in Section 2.2.2.2, page 21).

The *Length* variable refers to the travel length of the slider’s knob. The values are 20mm (small) and 70mm (long). To define the length, we computed the chord D between the points of the thumb’s rotation angle. The value was given by the following equation: $D = 2r \sin(\frac{\theta}{2})$, with r the radius, in this case the thumb’s length, and θ the angle subtended by the chord, in this case the thumb’s rotation angle. Hirota [67] found an average thumb’s length (r) of 60.4mm and an average rotation angle (θ) of 68.1 degrees. We obtain an average longest straight line (D) that the

thumb can perform of 70.16mm. Note that both 20mm and 70mm values are within the range of commercial sliders that vary in length from 15mm to 100mm.

Similar lengths were explored on a re-sizable tangible slider in [34], but the slider was manipulated through a pinch gesture of the thumb and index fingers. On the contrary, we aim to explore the pointing resolution of the thumb alone for different slider’s lengths.

Given these conditions, we hypothesize the following:

H1: The *tilted* orientation will outperform the *vertical* orientation since it facilitates the thumb’s movements.

H2: The *long* sliders will outperform the *small* sliders due to their larger motor space, based on previous work by Chapuis & Dragicevic [26].

5.2.1 Apparatus and Participants

We built four prototypes (see Figure 5-2): two versions of the vertically oriented sliders (A and C) and two versions of the tilted slider (B and D). For each orientation, we built two prototypes, each of them with a different sliding range: short (A and B) and long (C and D). For the prototypes, we used the following Bourns sliders [19]: PTA2043-2015CPB103 (with a 20mm sliding range) and PTB0143-2010BPB103. The later has a sliding range of 100mm that we cut to obtain a sliding range of 70mm, as shown in Figure 5-2, C-D. For the vertical orientation, we placed the sliders in the middle of the prototype in order to evaluate the performance of the long-vertical slider when reaching for targets outside the thumb’s functional area. Mobile applications like X32q [11] make use of sliders in the middle of the screen.

Except for their sliders, all prototypes had the same dimensions: 137mm (height) \times 66mm (width) \times 20mm (thickness). The length and width were the ones of a modern smartphone in order to support a similar grip as the one on a phone. Prototypes were built using 3mm-thick laser-cut medium-density fiberboard.

We remind the reader that the goal of this and the following studies is to analyze the interaction with mobile devices that enable operation with tangible controls on

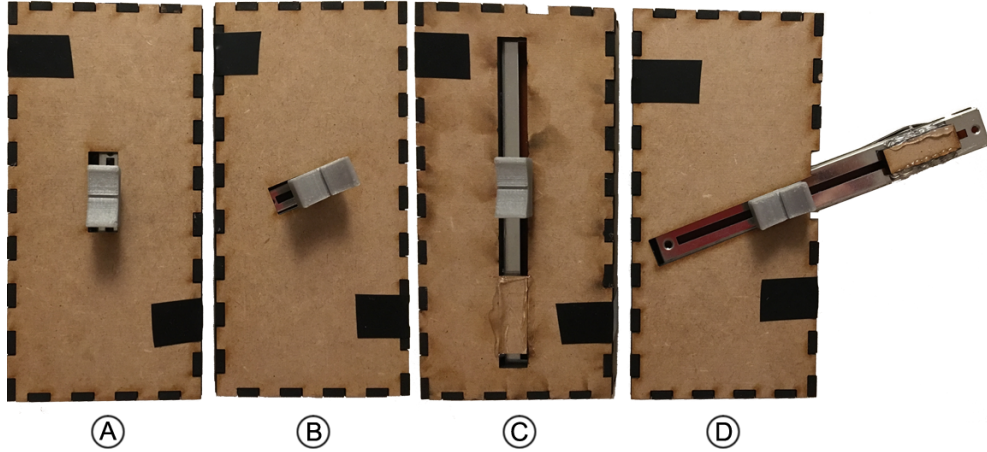


Figure 5-2: Prototypes: (A) small vertical slider, (B) small tilted slider, (C) long vertical slider and (D) long tilted slider.

its surface. Therefore, we kept the form factor of the prototypes as similar as possible to those of commercial smartphones. Our vision of the mobile device of the future enables the flexibility of a graphical interface and the affordance and tactile benefits of tangibles. Thus, we discarded physical remote controls since they provide a static layout of controls. Moreover, we considered a slider that goes beyond the frame of the prototype while still remaining in the thumb's functional area.

In order to communicate with the experimental software, the prototype was connected to an Arduino Mega 2560 board. The board was connected via a USB cable to a 15-inch MacBook Pro laptop running the experimental software. The experimental software displayed the pointing tasks on a Retina screen with 110 pixels per inch.

Ten volunteers (22-33 years old, $M=27.2$, $SD=3.1$, 7 males and 3 females) were recruited on campus. All were right-handed and owners of touchscreen phones. The average finger span (distance between the index finger and thumb) of the participants was 165mm. The average measured index finger's length was 81mm.

5.2.1.1 Task

Participants needed to perform a pointing task on distant targets (see Figure 5-3). This task is inspired from previous studies, e.g., [9, 24, 34, 138, 188]. We have chosen

this abstract task in order to represent a real life task (e.g., filtering data in a wall-size display, see Section 2.4, page 33) in which the user needs to adjust a distant parameter without looking at the input device in her/his hand.

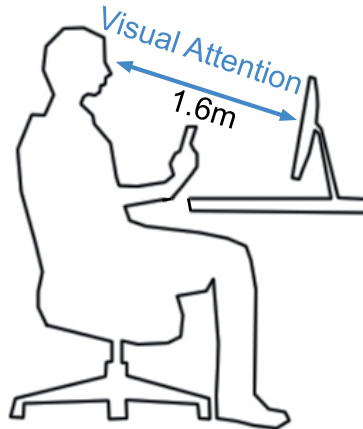


Figure 5-3: Participant is sitting in front of a distant screen holding the prototype. The visual attention is on the screen on which the experimental task is displayed.

For the user to perform the task, we displayed a graphical slider (see Figure 5-4), on a distant screen at 1.6m from the participant. The participant controlled the cursor with our prototypes. The graphical slider had a length of 140mm/606px. The user's cursor is a thin horizontal line that the user can vertically control. A visual feedback of the error (in red on Figure 5-4) from the user's cursor to the target area is displayed along the slider.

The distance between targets was 100mm/433px and each target had a width of 7mm/31px. Participants needed to perform back and forth movements to reach the targets. For instance, if the starting target appeared at the bottom of the slider, the following target will appear at the top and the next one at the bottom. The used distance and target's width define a Fitts' law Index of Difficulty (ID) of 4. This value was given by $ID = \log_2(\frac{D}{W} + 1)$, where D is the distance between the user's cursor position and the target, and W is the target width. The chosen ID avoided the task being too difficult [148]. The Control-Display gain of the long sliders (CD

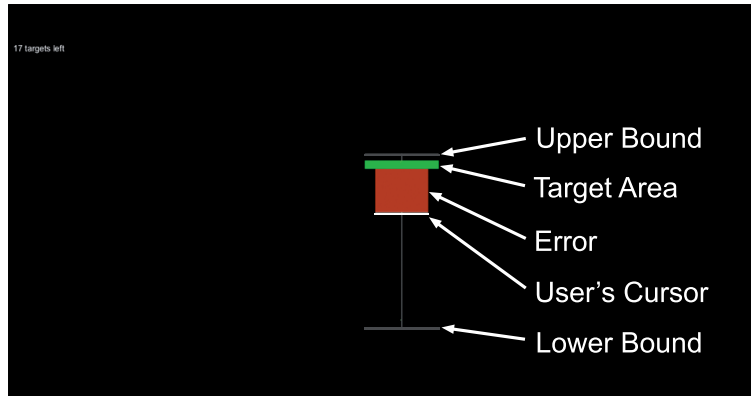


Figure 5-4: Screen shot of the experimental pointing task with a graphical slider of 140mm/606px, a target’s width of 7mm/31px, and a distance of 100mm/433px.

gain = 2) and the small sliders (CD gain = 7) are within the range of the CD gain that does not affect significantly the movement time [24].

As in previous work (e.g., [34]), the task must be successfully completed. The error rate is then forced to zero. Participants were asked to be as fast as possible while pointing.

To validate their task, we asked participants to maintain the cursor within the target area for 1 second. This mechanism avoids any additional error-prone actions to validate the pointing [166]. Before analyzing the data, we subtracted the extra second for validation from the movement time.

After the task is completed successfully, a new target appears in a predefined distance of 100mm/433px according to the current location of the user’s cursor.

5.2.2 Procedure

First, participants were introduced to the four prototypes through a training phase. We asked participants to find a comfortable handgrip in which they could operate the large-tilted, small-tilted, and small-vertical conditions without changing the handgrip. Participants were asked to perform the task as fast and precise as possible. During the training phase, participants were able to perform the tasks until they notified the experimenter that they were ready to start the experiment. The order of presentation

of the prototypes was randomized. After the training, the trials started.

The tasks were divided in 4 blocks representing the 4 possible combinations of the Orientation \times Length conditions. The four blocks were presented to the participants in random order. A small break was given to participants after each block. For each block, 17 repetitions of the pointing task were performed. The first repetition was not considered in the analysis: by doing so, we avoided having results affected by the knob's position from the previous block. This gives 8 forward and 8 backwards movements on the slider to reach the target. The study ended with a System Usability Scale (SUS) test [122] given to the participants in order to capture the perceived usability of the four sliders.

A total of 640 measures of movement time were collected, by 10 participants \times 16 repetitions \times 2 orientations \times 2 lengths. For each Orientation \times Length conditions, this resulted in 160 measures of movement time.

5.2.3 Measures

The main objective in this experimental study was to determine the impact of the properties (orientation and length) of tangible sliders on performance. To this end, we recorded the movement time from the beginning of each task until the validation of the target area.

In addition to this measure, the actions of the participants were video-recorded in order to study how they interact with the prototypes. We annotated all the initial handgrips and the movements performed by the fingers on the back of the device. The recordings also captured the focus point of their visual attention to verify that they were not looking at the prototypes during manipulation.

Finally, as an indication of perceived usability of the 4 sliders (2 Orientations \times 2 Lengths), we asked them to fill in a SUS questionnaire (see Appendix B.1 for an example of a filled SUS questionnaire).

5.2.4 Results

Following Sauro *et al.* [141] recommendation, we used the geometric mean to estimate the center of the distribution of the movement time. Trials were aggregated per participant and the Orientations \times Lengths combination. A Shapiro-Wilk test revealed that we could assume the normality of the data ($W = 0.9$, $p > 0.05$). This allowed us to run repeated measures ANOVA.

The repeated measures two-way ANOVA shows that Length ($F(1, 36) = 50$, $p < 0.0005$) had a significant impact on movement time. On the contrary, Orientation ($F(1, 36) = 0.22$, $p > 0.05$) had no significant impact on movement time. Figure 5-5 presents the mean movement time of the four sliders. For both Orientation conditions, the long sliders outperformed the small sliders (-0.6s). On average, the vertical and tilted conditions presented similar movement times (1.32s and 1.81s on long and small sliders respectively).

ANOVA revealed no significant differences regarding usability between the conditions of the Orientation and Length variables ($F(3, 28) = 0.74$, $p > 0.05$). However, the SUS questionnaire revealed that the long-vertical slider was found the most usable by the users (76.87/100, 56.5% after normalization [21]), followed by the small-vertical slider (73.75/100, 54.2%). Both tilted sliders were perceived similarly (68.75/100, 50.5%).

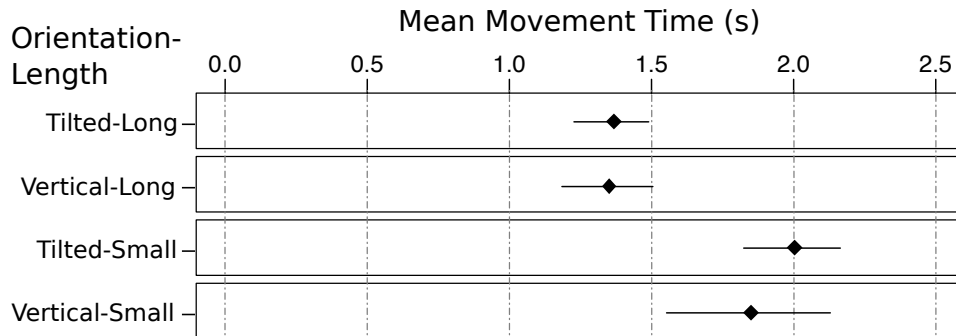


Figure 5-5: Mean movement time (x-axis) for the combination of the Orientation and Length conditions (y-axis). Error bars show 95% confidence intervals.

5.2.5 Discussion

5.2.5.1 Vertical Orientation for Small Sliders

For small sliders, the vertical orientation proved to be slightly more efficient (-0.15s) than the tilted orientation, discarding H1. Since both Orientations fit within the comfortable area of the thumb, this suggests that flexion-extension movements of the thumb perform better than adduction-abduction movements. This further enriches the results from Karlson *et al.* [85], which encourage the use of orthogonal movements rather than diagonal ones for thumb interaction.

Surprisingly, the time difference is marginal between the two Orientations on the long sliders. We observed that all participants changed the grip of the device –i.e. tilting the prototype (see Section 2.2.2.3, page 25)– while interacting with the long-vertical slider in order for the thumb to reach the target. On the contrary, all the participants kept the same grip while interacting with the long-tilted slider. This suggests that changing the grip of the device, to reach out to targets outside the comfortable area of the thumb (see Figure 5-6, D), has little impact on movement time.

Regarding the research question introduced at the beginning of this chapter (page 81), these results suggest that sliders should keep a vertical orientation when fitted into the thumb’s functional area.

5.2.5.2 The Length of the Slider is Important

The slider’s length proved to impact the movement time. On average, the long sliders performed 0.6s faster than the small sliders, supporting H2. We argue that this difference is due to the difficulty of performing the task with a small motor space. The task is significantly more difficult with small tangible sliders in time (+0.59s). This result support previous work on motor space scaling (i.e. shrinking the target’s size in the motor space) as described in Section 2.3.2, page 30.

Regarding the research question introduced at the beginning of this chapter (page 81), these results suggest that fitting the slider into the thumb’s functional area has

a negative impact on performance.

5.2.5.3 Eyes-free Interaction and Preference

Video footage of the experiment revealed that participants were able to perform the task with the four prototypes without the need to look at the input device. This observation supports the results presented in Section 4 (page 73) about tangible user interfaces for the control of distant continuous parameters.

The SUS questionnaire revealed that the long-vertical slider was found the most usable by the users, followed by the small-vertical slider. This could be explained by the familiarity of the orientation for a slider. Moreover, some participants commented that they prefer the vertical orientation because it resembles swipe gestures of touch interaction. However, several participants commented that the long-tilted slider was more comfortable to use: *“I found the tilted one more suitable with the thumb, because it’s in the same direction of the motion”*; *“I’d choose the long-tilted one for one-handed task for its better ergonomics”*; *“I liked more the tilted one because it was easier to use with one hand”*; *“For one hand, I found the long-tilted slider easier to manipulate”*. This suggests that operating outside the functional area of the thumb requires uncomfortable handgrips.

5.2.5.4 Thumb Interaction: Three Levels of Difficulty

Based on the comments collected from the participants and the thumb’s movements model from Karlson *et al.* [85] (section 2.2.2.2, page 21), we support the concept of different difficulty levels for thumb interaction when using a mobile device with a single hand. We suggest three difficulty levels (see Figure 5-6):

- *Easy* difficulty level: this level is defined by the area in which targets are directly reached by the thumb without handgrip changes, namely, the functional area of the thumb (see Section 2.2.2.2.1, page 22).
- *Medium* difficulty level: this level is defined by the area in which uncomfortable handgrip changes are required to reach targets. We suggest the further the

target is from the easy difficulty level, the stronger the negative impact on performance is.

- *Hard* difficulty level: this level is defined by the area in which hand relocations are required to reach targets. We suggest that in this area targets are far enough from the easy difficulty level to always provoke a strong negative impact on performance.

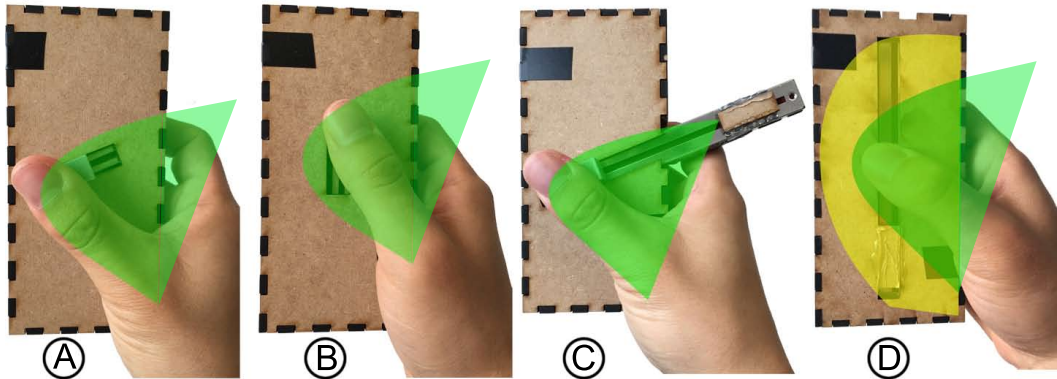


Figure 5-6: The *Easy* difficulty level (in green) and the *Medium* difficulty level (in yellow) of the functional area of the thumb for the four prototypes. Inspired from [71].

In our experiment, for both small sliders, the operation range was kept by design within the *Easy* difficulty level of the functional area of the thumb (see Figure 5-6, A-B). No change of grip was required. For the long-tilted slider, its orientation avoided any change of grip and thus, it remained in the *Easy* difficulty level (see Figure 5-6, C). Only the long-vertical slider required a change of grip in order to operate it. As a consequence, only the long-vertical slider defined the *Medium* difficulty level of the functional area of the thumb (see Figure 5-6, D). However, this work does not explore the operating range of the *Medium* difficulty level and thus, the *Hard* difficulty level threshold.

5.2.6 Summary of Experiment: Impact of the Slider’s Orientation and Length on Performance

Overall, the length of the slider (motor space) impacts significantly the performance. Long sliders (70mm) outperform small sliders (20mm). Among the long sliders, the handgrip changes provoked by the vertical slider show no significant difference in performance with the tilted slider. Furthermore, participants find more usable the vertical sliders than the tilted ones.

Given these results, we define the boundaries between the difficulty levels of the functional area of the thumb as following: the *Hard* difficulty level as the area in which the change of grip dramatically affects the performance. The *Medium* difficulty level is the area in which a change of grip could affect the performance. Finally, the *Easy* difficulty level is the area in which users do not need to change their grip to fulfill the task. This corresponds to the so called functional area of the thumb as we defined in Section 2.2.2.2.1 (page 22). This experiment called for a followed up experiment (see Section 5.4) in which the hand movements required at the *Medium* and *Hard* difficulty levels of the functional area of the thumb are further explored in more detail.

Regarding the research question introduced at the beginning of this chapter (page 81), we concluded that reducing the slider length to fit within the functional area of the thumb is not a viable solution due to the scaling effect of the motor space. Moreover, changing the orientation of long sliders has no significant impact on performance. We therefore decided to explore the second approach which consists of enhancing the reachability of the thumb.

5.3 Enhancing the Reachability of the Thumb

In the previous section, we adopted an approach that consists of bringing targets closer to the thumb’s functional area in order to facilitate one-handed interaction.

As explained in Section 3.2 (page 60), a complementary approach consists of enhancing the thumb’s reachability to access all the areas of the interface.

As described in Section 3.2.2 (page 65), several studies led to new interaction techniques that enable users to reach far targets from within the thumb’s functional area. For instance, by making use of an extendable cursor [138] or performing thumb gestures to shorten the distance to the aimed target [158]. All these techniques are graphical. In our research, to support eyes-free interaction, we consider tangible controls. Our approach is then to consider shape-changing tangible controls to enhance the reachability of the thumb.

Inspired by the related work, we present our second interaction technique for eyes-free one-handed interaction: an extendable slider capable of extending its knob length (see Figure 5-7). The slider’s knob increases its length in order to support thumb-clutching movements. When the knob is moved upwards, the knob actuates downwards while letting the slider’s landmark go upwards (see Figure 5-7, A-B and C-D), and vice versa.

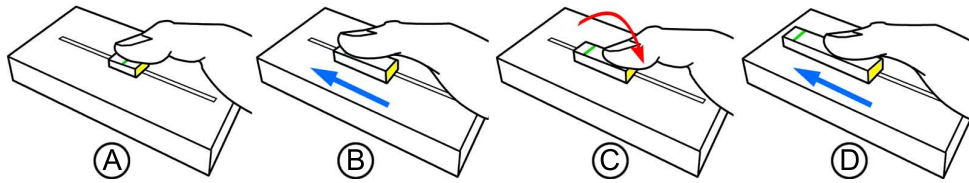


Figure 5-7: Clutching with an extendable tangible slider: (A) the user places her thumb on the slider knob and (B) begins to push upwards (direction of the blue arrow). (C) When this action is no longer comfortable the user is able to continue to adjust the controlled parameter (as visualized with the 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 knob expands (yellow side) in the opposite direction.

We opted for a clutching design instead of a rate-based design (i.e. isometric controls that map input to a velocity vector and move the display pointer in the specified direction and speed) since the former offers a high degree of perceived usability [181]. Clutching allows us to provide a long motor scale [26] while maintaining thumb’s movements within its comfortable area. A long motor scale a key property on tangible controls as observed in the previous section 5.1 (page 82). Users can then always

manipulate the knob precisely, eyes-free, and comfortably, i.e., the *Easy* difficulty level of the functional area of the thumb (see Section 5.2.5.4, page 92). Moreover, the tangible aspect of the slider allows operation without looking at the device. In Table 5.3, this technique, namely extendable tangible slider, is positioned in our design space of Chapter 3.

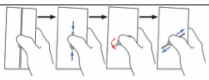
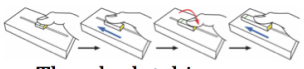
	Bringing elements closer to the thumb			Enhancing the thumb's reachability		
	Front	Back	Lateral	Front	Back	Lateral
In-air						
Touch-based						
Tangible	 <p>Changing the orientation and length of tangible sliders</p>			 <p>Thumb-clutching on a extendable tangible slider</p>		

Table 5.2: The extendable tangible slider positioned in the design space for eyes-free one-handed interaction on mobile devices: Enhancing the thumb's reachability (x-axis); Tangible interaction (y-axis); Front side (z-axis).

To study extendable tangible sliders, we proceeded into three steps:

1. We studied the impact of thumb-clutching movements on performance in comparison with other hand movements (i.e. handgrip changes and hand relocations) required by conventional tangible sliders. To do so, we performed an experiment that is described in Section 5.4 (page 97).
2. Based on the promising results, we then designed a first extendable tangible slider that we experimentally evaluated in Section 5.5 (page 107).
3. Finally, we studied the impact that the actuation motion of the extendable tangible slider has on eyes-free interaction. To do so, we performed a third experiment that is described in Section 5.6 (page 118).

5.4 Experiment 1: Studying Handgrip Changes, Hand Relocations and Clutching

As explained in Section 2.2.2.3 (page 25), two hand movements are observable when reaching targets outside the thumb’s functional area: 1) handgrip changes which involve the tilting of the device and changing the position of the fingers on the back of the mobile device, and 2) hand relocations which require relocating the whole hand along the mobile device. In this first experiment, we focus on comparing handgrip changes and hand relocations with thumb-clutching movements. For this, we compared thumb-clutching, performed on a large knob, with handgrip changes and hand relocations, caused by conventional tangible sliders. A within-subject design was used with three independent variables: *Knob*, *Distance* between targets and *Width* of the target.

The *Knob* is used on a mobile device to control a graphical cursor displayed on a distant screen. The Knob variable is composed of two conditions (see Figure 5-8):

- Small (20mm × 10mm × 23mm): It resembles a conventional tangible slider. The knob require users to perform handgrip changes and hand relocations to acquire targets over medium and long distances respectively (see Figure 5-8, A-B).
- Large (150mm × 10mm × 23mm): This is meant as a low-fidelity prototype of an extendable slider. The knob allows reaching targets outside the thumb’s functional area by performing thumb-clutching movements inside the functional area, i.e., the *Easy* difficulty level described in Section 5.2.5.4, page 92 (see Figure 5-8, C).

The *Distance* variable represents the distance between targets displayed on a distant screen. To explore targets that force handgrip changes and hand relocations, we choose 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 (see Section 5.2, page 84); second, 217mm between consecutive on-screen targets (i.e.

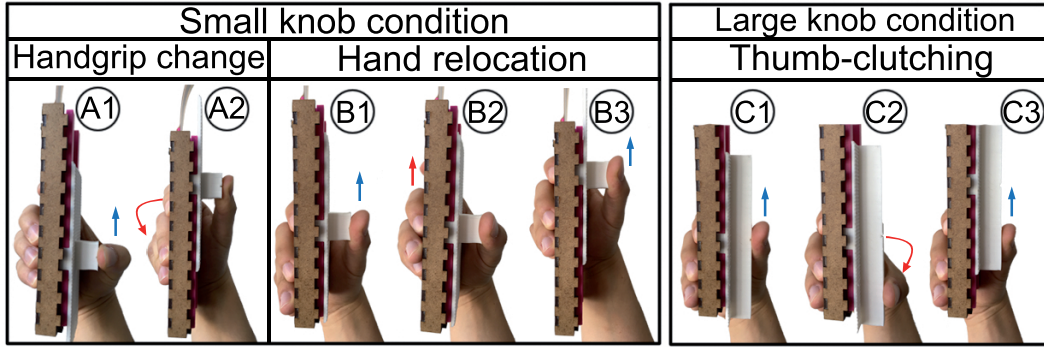


Figure 5-8: The Knob conditions and the hand movements related to their operation: (A1) the small knob is pushed (direction of the blue arrow) with an initial handgrip. (A2) The fingers on the back of the device move (direction of the red arrow), thus changing the handgrip. (B1) the small knob is pushed (direction of the blue arrow) with an initial handgrip. (B2) The hand is relocated (direction of the red arrow) when the thumb’s limit is reached. (B3) The knob is pushed with the new hand location. (C1) The large knob is pushed (direction of the blue arrow) with an initial handgrip. (C2) Relocation of the thumb. (C3) The knob is pushed with the same handgrip.

150mm in the control space on the mobile device) proved to force the relocation of the hand. To find this value, we performed a pilot test to observe the distance between targets that requires hand relocations. Both distances fit within modern large sized mobile phones [5].

The *Width* variable represents the target’s width. In order to analyze performance from coarse to fine adjustments, two different widths are used: 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 [148]. This confirmed our choice by preventing the task being too difficult [148].

We then hypothesize that:

- H1: When pointing at closest targets, thumb-clutching (large knob) and handgrip changing (small knob) perform equally;
- H2: When pointing at farthest targets, thumb-clutching (large knob) outperforms hand relocations (small knob);
- H3: When pointing at smallest targets, thumb-clutching (large knob) outperforms

both handgrip changes and hand relocations (small knob).

5.4.1 Apparatus and Participants

A single body for the prototype (see Figure 5-8) was built with the following dimensions: 150mm (height) \times 70mm (width) \times 17mm (thickness), giving a total thickness of 40mm when using the knobs. The length and width were the ones of a commercial large phone [5] for a realistic grip. The prototype was built using a 3mm-thick laser-cut medium-density fiberboard. A membrane potentiometer [149] of 200mm length captures the position of the slider's cursor. The slider and the knobs were made with an Ultimaker 2+ 3D printer, using PLA as filament. A large plate surrounded the knobs in order to help the stabilization of the knobs during manipulation. The potentiometer was connected to an Arduino Mega 2560 board. The board was connected via USB to a MacBook Pro running the experimental software, displayed on a 27-inch Thunderbolt screen (2560 \times 1440, 109ppi).

Sixteen volunteers (between 23 and 34 years old, M=27.3, 11 males and 5 females) were recruited on campus. All were right-handed and owners of touchscreen phones.

5.4.2 Task

The study required participants to perform a distant pointing task. As explained in Section 5.2.1.1 (page 86), this abstract task is representative of a real life tasks in which users adjust a distant parameter without looking at the mobile input device (e.g., browsing a list of channels displayed on the TV).

The experimental task consisted of the user controlling the input device without looking at it. The visual focus was on a screen placed at a distance of 1.60m. The mobile device controlled the cursor of a graphical slider displayed on the distant screen (see Figure 5-9). The graphical slider had a length of 232mm. The cursor, controlled by the user, was displayed as a white horizontal line (see Figure 5-9). A visual feedback of the remaining distance (in red) from the user's cursor to the target (in green) is displayed along the slider. Participants were asked to point as fast and

accurate as possible.

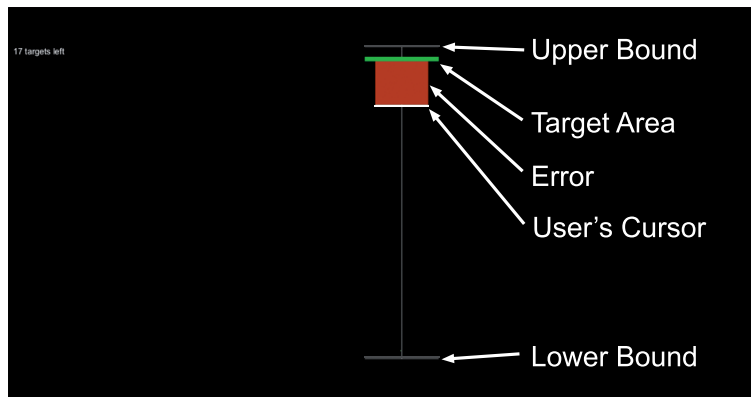


Figure 5-9: Screenshot of the experimental pointing task with a slider of 232mm/1121px, a target's width of 1.6mm/7px, and a distance of 217mm/1048px.

For validation, we asked users to maintain the cursor in the target area for 1s. As explained in Section 5.2.1.1 (page 86), this validation mechanism is used to avoid any additional error-prone actions [166]. The extra second was subtracted from the movement time before analysis. Overshoots (i.e. passing over a target – entering and leaving the target area) are used to indicate pointing accuracy [166]. After the task is completed successfully, a new target appears at a predefined Distance (116mm or 217mm) from the current location of the user's cursor.

5.4.3 Procedure

First, participants were introduced to the prototype through a training phase in which they were able to perform the tasks with the different combinations Knob \times Distance \times Width. Participants were asked to perform the task as fast and precise as possible. During training, the order of presentation of the conditions was randomized. The training phase lasted 10 minutes on average. After the training phase, the trials started.

The tasks were performed in 2 blocks, one per Knob condition. Half of the participants started with the small knob and continued with the large knob, and vice versa for the other half of the participants. Each block was divided in 4 sub-blocks

representing the 4 Distance \times Width combinations. The presentation order of the sub-blocks was randomized. For each sub-block, participants performed 17 repetitions of the task. The first repetition was not analyzed to avoid having results affected by the knob's position from the previous sub-block. A small break was allowed after each sub-block. After participants completed the task for the 2 blocks, they were given a SUS [122] questionnaire to fill in.

A total of 2048 measures of movement time were collected, from 16 participants \times 16 repetitions \times 2 knobs \times 2 distances between targets \times 2 target's widths. This resulted in 256 measures for each Knob \times Distance \times Width condition.

5.4.4 Measures

Our main objective in this study was to determine the impact of thumb-clutching (large knob), handgrip changes and hand relocations (small knob) on performance. To this end, we recorded the movement time from the beginning of each task until the validation. In addition, we recorded the number of performed overshoots in order to study the accuracy of the hand movements (as done in [166]). The actions of the participants were video-recorded to study the required hand movements to operate the prototypes (i.e. handgrip changes and hand relocations for the small knob). Finally, as an indication of perceived usability of the tested knobs, we asked them to fill in a SUS questionnaire [122].

5.4.5 Results

Following Sauro *et al.* [141] recommendation, we used the geometric mean to estimate the center of the distribution of the movement time. Trials were aggregated using the factors Knob, Distance, and Width for each participant. A Shapiro-Wilk test revealed that we could not assume the normality of the data ($W = 0.9$, $p < 0.001$). Thus, we applied an Aligned Rank Transformation on the data [178] and then ran repeated measures ANOVA on the aligned ranks to investigate possible interactions between factors.

A three-way ANOVA shows that Knob ($F(1, 105) = 32.9, p < 0.0001$), Distance ($F(1, 105) = 191.9, p < 0.0001$) and Width ($F(1, 105) = 634.4, p < 0.0001$) had a significant impact on movement time (see Figure 5-10). An interaction between Width and Distance ($F(1, 105) = 4.8, p < 0.05$) proved to be significant. This confirms that the Width values were appropriate to distinguish between fine and coarse adjustment for the Distance values.

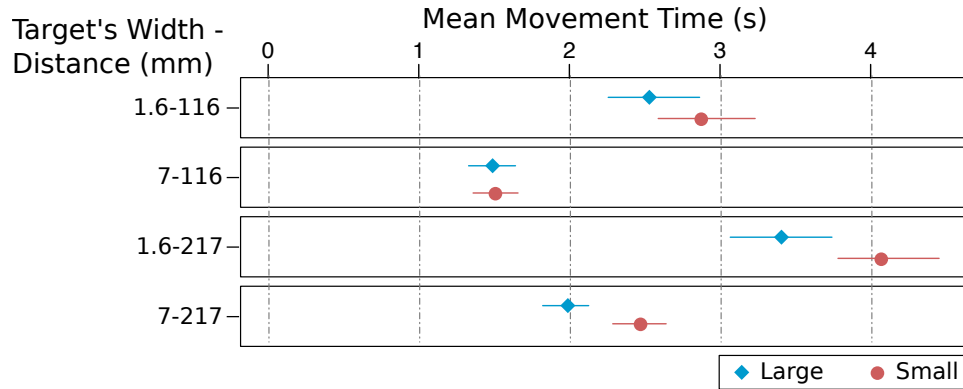


Figure 5-10: Mean movement time for the 2 Knob conditions and for the 4 possible Distance \times Width conditions (y-axis). Error bars show 95% confidence intervals.

An interaction between Knob and Distance ($F(1, 105) = 8.5, p < 0.01$) proved to be significant. For the 217mm Distance condition, the large Knob performed faster for both 1.6mm and 7mm target's Width (-0.6s and -0.4s respectively) than the small Knob. A Tukey's post-hoc test revealed a significant difference between the large and small Knob conditions ($t(105) = 5.7, p < 0.001, \text{Cohen's } d=0.5$). For the 116mm Distance condition, the large Knob performed better (-0.4s) than the small Knob for a target's Width of 1.6mm. For the 7mm target's Width, the large and small Knobs performed equally. These differences in movement time are observable in Figure 5-10.

To explain the equal performance between Knob conditions for the single 7mm \times 116mm condition, we used the video footage. We compared the amount of thumb-clutching and handgrip changes performed at each repetition of the task. On average, 1 clutching movement on the large Knob was required ($SD=0.4$). Only 1 handgrip change was required on the small Knob. This gives a total of 64 handgrip changes

for the small knob. On the contrary, thumb-clutching performed with the large knob avoids handgrip changes. This is important since a study from Eardley *et al.* (see Section 2.2.2.3, page 62) found a correlation between handgrip changes and the perception of security (i.e. risk of device being dropped) for different body postures. In the study, participants rated the likelihood of dropping the mobile phone from the operating hand/s at different body postures. When standing, 30 handgrip changes were graded 4 in a 7pt likert scale regarding the likelihood of dropping the mobile device, and when lying 100 handgrip changes were graded 1.6 (being 1 the least secure).

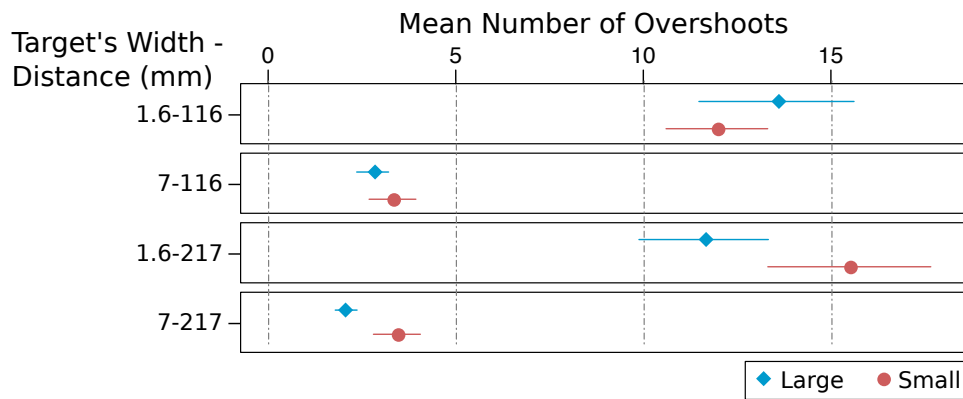


Figure 5-11: Mean number of overshoots for the 2 Knob conditions and for the 4 possible Distance \times Width conditions (y-axis). Error bars show 95% confidence intervals.

Regarding the number of overshoots (see Figure 5-11), on average, for large targets (7mm) and long distances (217mm), participants overshoot 2 times (SD=0.02) with the large knob, and 4 times (SD=0.03) with the small knob. For large targets and short distances (116mm), participants overshoot 3 times (SD=0.03) with the large knob, and 4 times (SD=0.04) with the small knob. For small targets (1.6mm) and long distances, participants overshoot 13 times (SD=0.09) with the large knob, and 17 times (SD=0.13) with the small knob. For small targets and short distances, participants overshoot 15 times (SD=0.13) with the large knob, and 12 times (SD=0.09) with the small knob. This suggests that thumb-clutching movements are slightly more precise than hand relocations and handgrip changes for: 1) large targets for both distances

between targets, and 2) small targets and long distances. For small targets and short distances, handgrip changes are slightly more precise.

Regarding the usability, SUS indicates that the small knob (69/100, 51% when normalized [122]) is perceived slightly more usable than the large knob (65/100, 48%). However, ANOVA revealed no significant differences regarding usability between the conditions of the Knob variable ($F(1, 30) = 3.44, p > 0.05$). This result contrast with the ones presented by Nancel *et al.* [117] in which participants found clutching movements as more usable than non-clutching ones on a trackpad.

5.4.6 Discussion

In this section we discuss the observed effects that had an impact on the performance.

5.4.6.1 Short Distances: Thumb-clutching vs. Handgrip Changes

For small targets (1.6mm) near the functional area of the thumb (116mm), thumb-clutching movements done with the large knob outperform handgrip changes done with the small knob (-0.4s). Moreover, participants were also more precise with thumb-clutching. Participants overshoot 9 times more on average with the small knob, which implied handgrip changes, than with the large one.

Regarding large targets (7mm), result suggests that for non-difficult pointing tasks, thumb-clutching movements and handgrip changes perform equally well.

Overall, thumb-clutching movements outperform handgrip changes for small targets and lead to similar performance than handgrip changes for large targets. We consequently partially support H1 (section 5.4, page 97).

5.4.6.2 Long Distances: Thumb-clutching vs. Hand Relocations

Similarly to short distances, for small targets (1.6mm) outside the thumb's functional area (217mm), thumb-clutching movements done with the large knob outperform hand relocations done with the small knob (-0.6s). Moreover, participants overshoot 9 times more on average with the small knob than with the large knob. This result

suggests again greater precision with the large knob than with the small knob.

Regarding large targets (7mm), thumb-clutching outperforms hand relocations (-0.5s). This result suggests that a hand relocation is more time consuming than a thumb-clutching movement. We argue that it is caused by 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 relocation is slower and less precise than thumb-clutching when pointing outside the functional area of the thumb; supporting H2 (section 5.4, page 97).

5.4.6.3 Small Targets

Thumb-clutching movements outperform handgrip changes and hand relocations when acquiring 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 (with less overshoots); supporting H3 (section 5.4, page 97).

5.4.6.4 Usability

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

5.4.7 Summary of Experiment 1: Studying Handgrip Changes, Hand Relocations and Clutching

Overall, thumb-clutching movements perform well for targets beyond the *Easy* difficulty level of the functional area of the thumb, in spite of the idle time while the thumb clutches. This supports the results about clutching on relative pointing devices

[117]. Furthermore, operation in a thumb-clutching manner allows users to manipulate the device with a stable handgrip. We confirmed this by examining video footage of participants operating the large knob, in which no handgrip change was present.

Operating tangible sliders in absolute pointing manner produces: 1) handgrip changes when targets are near the borders of the functional area of the thumb, and 2) hand relocations when targets are far from the functional area of the thumb. This result supports the three difficulty levels of the functional area of the thumb previously discussed in Section 5.2.5.4, page 92. In Figure 5-12 we illustrate the difficulty levels of the functional area of the thumb and the required hand movements for each level.


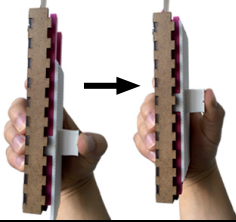

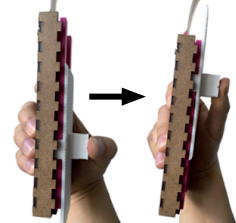

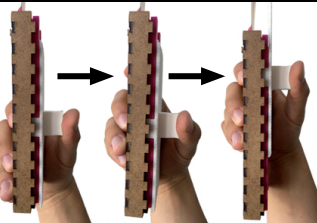
Difficulty Level	Covered Area	Required Hand Movements
EASY		
MEDIUM (116mm)		
HARD (217mm)		

Figure 5-12: Diagram of the three difficulty levels of the functional area of the thumb and the hand movements required at each level.

Regarding the research question introduced at the beginning of this chapter (page 81), the results of this study show that thumb-clutching movements are performed inside the thumb’s functional area, thus preventing handgrip changes and hand relocations. Moreover, a clutching approach is compatible with long sliders which offer

better performance than small sliders due to their larger motor scale (as explained in Section 5.2).

In this experiment, we studied clutching with a low-fidelity prototype of an extendable tangible slider composed of large knob. However, even on a future miniature prototype, the knob has to be large in order to allow clutching. Unfortunately, a large knob hinders portability of the solution. In the following section, we explore a solution with a smaller knob. For this, we introduce actuation: we build a prototype that actuates the location of a small knob so that it moves back in the functional area of the thumb after clutching.

5.5 Experiment 2: Clutching with an Actuated Tangible Slider

Thumb-clutching proved to perform well when acquiring targets over medium and long distances while offering a stable handgrip. In Section 5.4 (page 97), the tested prototype involves a large knob. We go one step further to define a higher fidelity prototype. For this, we introduce actuation: we built a prototype that actuates the location of a smaller knob so that it moves back in the functional area of the thumb to support clutching.

We experimentally evaluate this prototype. We are particularly interested in studying the impact that the motion of the actuated knob has on the performance of thumb-clutching movements. In addition, we analyze the perceived usability of such a device.

5.5.1 Actuated Prototype

The starting point is to automatically move the knob of the slider back in the functional area of the thumb. The built prototype is formed by: 1) a base composed of the slider’s landmark and a FEETECH FS90R [42] continuous rotation servomotor with a pinion on its top, and 2) a long piece composed of a solid block, with a rack

on its back side, and a flat surface on top that serves as the slider's knob (see Figure 5-13).

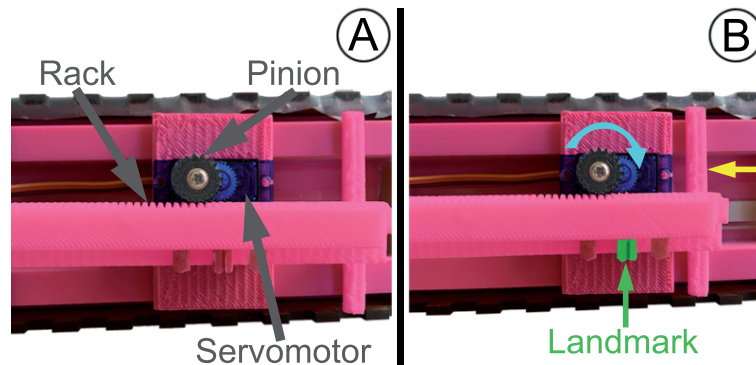


Figure 5-13: (A) The pinion-rack mechanism powered by the servomotor. (B) The rotational movement of the servomotor (blue arrow) is transferred to a bidirectional movement (yellow arrow), provoking the knob to slide. The landmark (in green) keeps the knob moving only forwards and backwards.

A pinion-rack mechanism locks the movement between the base and the long piece, hence, when the user pushes the knob upwards or downwards, the base moves in the same direction. This gives the sensation of directly pushing the slider's landmark. The mechanism also transforms the rotational movement of the servomotor to a bidirectional linear movement along the slider's axis (see Figure 5-13, B). The rotation of the pinion makes the solid block slide within the landmark. This simulates that the knob is getting larger upwards or downwards according to the current position of the landmark (see Figure 5-13). This allows the thumb to keep manipulating the slider without leaving its comfort area. The prototype presented an actuation time of 600ms which was the required time to move the knob back into the thumb's functional area when being pushed. The actuation started after crossing a threshold located at the center of the slider's length (80mm from the bottom).

As on any slider, the landmark indicates the current position/value of the knob. Two physical legs at both ends of the knob prevent the slider from bending when manipulated (see Figure 5-14). The knob is 23mm thick, giving a total thickness of 43mm with the prototype's body. The knob is 80mm long in order to stay within the

functional area of the thumb while reaching the extremes of the slider. The knob is 10mm wide to allow comfortable manipulation.

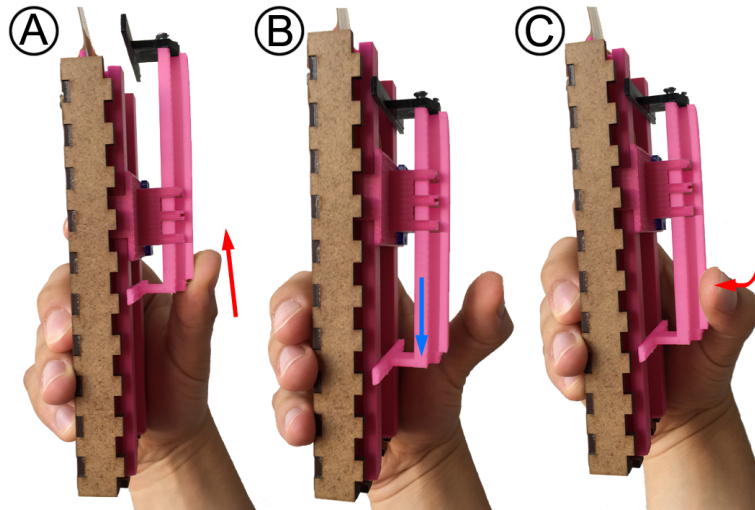


Figure 5-14: (A) The thumb pushes the knob (direction of red arrow) until it reaches its maximum elongation. (B) The knob starts to extend (direction of blue arrow) while the thumb clutches back to a comfortable position. (C) The thumb is within its comfortable area (direction of red arrow) and ready to continue operating.

5.5.2 Comparative Experiment

We performed the same experiment from section 5.4.2 (page 99). In comparison with the experiment of section 5.4, instead of considering a large knob, we tested the actuated tangible slider of section 5.5.1 (page 107). In this experiment we also consider a graphical slider in order to compare our tangible prototypes with the current available solution. The goal is to compare the performance of clutching when operating an actuated knob with hand movements (handgrip changes and hand relocations) when manipulating:

1. A non-actuated tangible conventional slider.
2. A graphical conventional slider which is the current available solution on mobile devices.

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:

- **Non-actuated:** It allows participants to operate the slider in an absolute pointing manner (see Figure 5-15, A);
- **Actuated:** It allows participants to perform thumb-clutching movements within the functional area of the thumb with a stable handgrip (see Figure 5-15, B);
- **Graphical:** It was used as a baseline in order to compare our proposed tangible solutions to the commonly used graphical solution (see Figure 5-15, C).

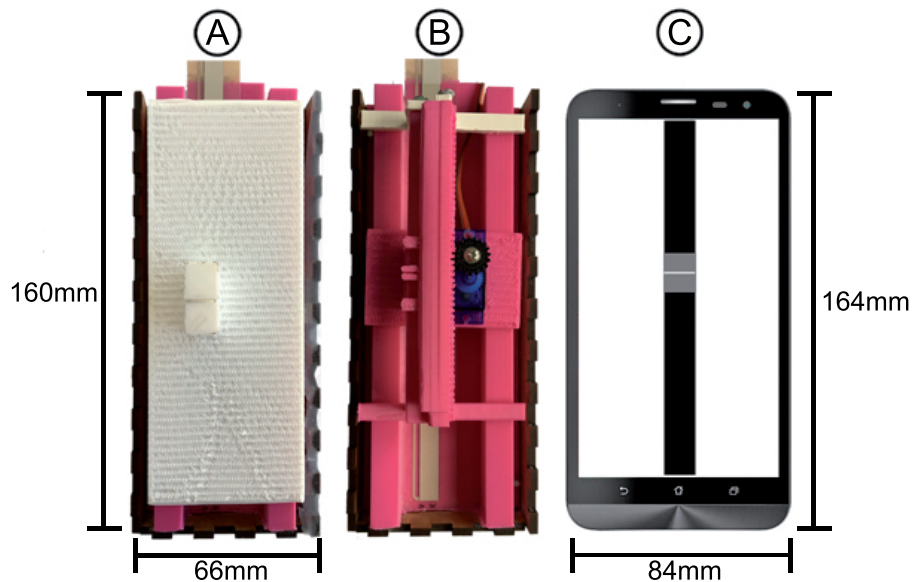


Figure 5-15: (A) The non-actuated knob behaves as a classic tangible slider. (B) The actuated knob allows thumb-clutching manipulation. (C) The graphical slider supports absolute pointing as the non-actuated slider.

Given the results of the experiment from section 5.4 (page 97), we hypothesize the following:

- H1: The non-actuated and graphical knobs will outperform the actuated knob for short distances between targets;

H2: The actuated knob will outperform the non-actuated and graphical knobs for large distances between targets.

5.5.3 Apparatus and Participants

The actuated and non-actuated slider knobs were printed with the Ultimaker 2+ 3D printer with PLA filament. The non-actuated tangible knob has the same design as the small knob from the experiment from section 5.4, page 97 (see Figure 5-15, A).

For the graphical slider, an ASUS Zenfone 2 Z E601KL (6 inches screen) smartphone was used. The smartphone's dimensions require participants to perform hand relocation movements when reaching the screen's upper and lower borders, i.e., the *Hard* difficulty level of Figure 5-12. The graphical knob has the same dimensions as the non-actuated knob, this is 20mm×10mm. We made use of the same experimental software and connection setup as in the previous experiment to operate the tangible prototypes. For the graphical slider, the communication with the experimental software was done through a Wi-Fi connection.

Fifteen volunteers (between 23 and 34 years old, M=28, 10 males and 5 females) were recruited on campus. 4 participants from the study of section 5.4 participated in this experiment.

5.5.4 Task and Procedure

For this experiment, participants performed the same task and followed the same procedure as in the previous experiment (see Section 5.4.2, page 99).

For the actuated condition, we asked participants to keep a stable and single handgrip near the center of the prototype's body. This was done to ensure that the slider's knob can always enter back the thumb's functional area.

A total of 2880 measures of movement time were collected, from 15 participants × 16 repetitions × 3 knobs × 2 target's widths × 2 distances between targets. For each Knob × Width × Distance conditions, this resulted in 240 measures of movement time.

5.5.5 Results

Following Sauro *et al.* [141] recommendation, we used the geometric mean to estimate the center of the distribution of the movement time. Trials were aggregated by participant and the factors being analysed. A Shapiro-Wilk test revealed that we could not assume the normality of the data ($W = 0.9, p < 0.01$). Thus, we applied an Aligned Rank Transformation on the data [178] and then ran a repeated measures ANOVA.

A repeated measures three-way ANOVA showed a significant main effect of Knob ($F(2, 154) = 9.5, p < 0.001$), Distance ($F(1, 154) = 224.5, p < 0.0001$) and Width ($F(1, 154) = 358.4, p < 0.0001$) on movement time. The differences in movement time between small (1.6mm) and large targets (7mm) for a same Distance confirm that the chosen conditions were appropriate to distinguish between fine and coarse adjustment (see Figure 5-16). Participants from the previous experiment performed, on average, 0.3s slower than the new participants ($SD=0.1$). This suggests that their previous experience had a limited impact on this experiment. An interaction between Knob and Distance ($F(2, 154) = 31.8, p < 0.0001$) proved to be significant. In light of this interaction, we continued the analysis of the Knob effects separately for each target's Width by two-factors ANOVAs, excluding the Distance factor.

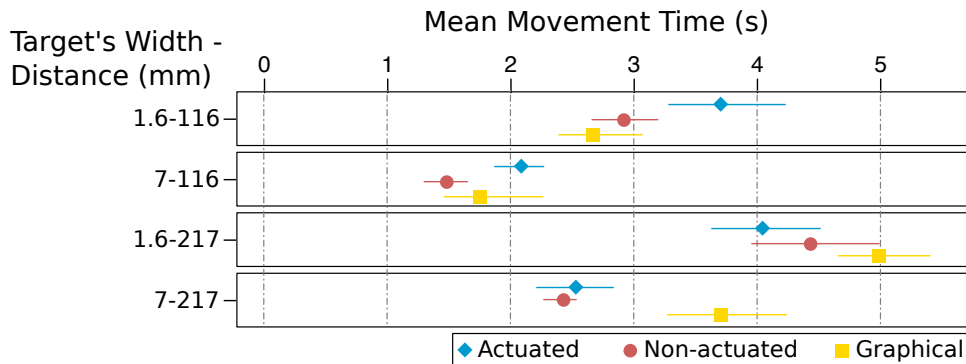


Figure 5-16: Mean movement time between the three Knob conditions for the 3 Width conditions (y-axis). Error bars show 95% confidence intervals.

5.5.5.1 Distance of 116mm: Handgrip Changes are Required

A significant effect was found for Knob ($F(2, 70) = 20.8, p < 0.0001$) and for Width ($F(1, 70) = 192.6, p < 0.0001$) on movement time. An interaction between Knob and Width proved to be significant ($F(2, 70) = 4.1, p < 0.05$). This interaction is observable in Figure 5-16 as the graphical slider is faster than the actuated slider for the 1.6mm Width condition and, for the 7mm Width condition, the mean performance time of the actuated slider enters the confidence interval of the graphical one. The actuated knob presents the highest movement time on both Width conditions. To confirm this observation we ran a Tukey's post-hoc test between the Knob conditions. The test revealed no significant difference between the graphical and non-actuated knobs for both Widths ($t(70) = 2.3, p > 0.03, \text{Cohen's } d=0.4$). However, the actuated knob showed significant differences with both non-actuated ($t(70) = 5.4, p < 0.0001, \text{Cohen's } d=1.8$) and graphical knobs ($t(70) = 5.7, p < 0.0001, \text{Cohen's } d=1.7$) for both Widths.

5.5.5.2 Distance of 217mm: Hand Relocations are Required

A significant effect was found for Knob ($F(2, 70) = 20.5, p < 0.0001$) and for Width ($F(1, 70) = 167.2, p < 0.0001$). To identify the impact that the Knob conditions had on movement time, we ran a Tukey's post-hoc test. The test revealed no significant difference on performance between the actuated and non-actuated knobs for both Widths ($t(70) = 0.5, p > 0.05, \text{Cohen's } d=0.2$). The graphical knob in comparison performed slower than the non-actuated knob ($t(70) = 5.2, p < 0.0001, \text{Cohen's } d=0.9$) and actuated one ($t(70) = 5.8, p < 0.0001, \text{Cohen's } d=0.7$) for both Widths. These differences are observable in Figure 5-16 where, for long distances between targets, the actuated and non-actuated knobs have similar performance times. The graphical knob presents the highest movement time on both width conditions.

5.5.5.3 Overshoots

Regarding the number of overshoots, on average, for large targets (7mm) and long distances (217mm), participants overshoot 2.6 times (SD=1.3) with the actuated slider, 3.2 times (SD=2.2) with the non-actuated slider, and 1.6 times (SD=1.2) with the graphical slider. For large targets and short distances (116mm), participants overshoot 5.4 times (SD=3.8) with the actuated slider, 3.4 times (SD=2.7) with the non-actuated slider, and 2.4 times (SD=1.7) with the graphical slider. For small targets (1.6mm) and long distances, participants overshoot 13.6 times (SD=6.4) with the actuated slider, 18.2 times (SD=9.1) with the non-actuated slider, and 10 times (SD=5.1) with the graphical slider. For small targets and short distances, participants overshoot 14.8 times (SD=8.6) with the actuated slider, and 13.4 times (SD=7) with the non-actuated slider, and 11.8 times (SD=5.5) with the graphical slider.

We expected that the smoother surface of the commercial phone used by the graphical slider would provide a higher accuracy level than the tangible sliders. Regarding the tangible sliders, the actuated slider provided a better accuracy than the non-actuated one when acquiring targets over long distances. This suggests that hand relocations negatively affect the accuracy level when operating a conventional tangible slider, particularly when acquiring small targets.

5.5.5.4 Subjective Results

The SUS scores indicate that participants found the graphical slider more usable (72/100, 53% after normalization [122]) than the actuated knob (66/100, 48%) and the non-actuated knob (62/100, 45%). ANOVA revealed a significant differences regarding usability between the Technique conditions ($F(2, 42) = 5.86, p < 0.01$). A Tukey's post-hoc test between the Technique conditions revealed no significant between the actuated knob and the graphical slider conditions ($p > 0.05$), and between the actuated and non-actuated knob conditions ($p > 0.05$). A significant difference was found between the graphical slider and the non-actuated knob conditions ($p < 0.01$). In addition to the perceived usability, five participants stated that they preferred the

actuated knob because they found it comfortable to use. Two participants preferred the non-actuated knob because of its tactile feedback, and one stated to prefer the graphical one due to its familiarity.

5.5.6 Discussion

In this section we discuss the observed effects that had an impact on the performance.

5.5.6.1 Tangibility Is Useful for Long Distances

The graphical knob performed as well as the non-actuated knob for the 116mm Distance condition, outperforming the actuated knob, thus supporting H1 (section 5.5, page 107). However, the actuated and non-actuated knobs outperformed equally the graphical knob on the 217mm Distance condition; thus, discarding H2 (section 5.5, page 107).

We explain the worst performance of the graphical knob for long distances with the amount of time participants looked down to reacquire the slider's knob. This effect has already been observed in Chapter 4 (page 73) when operating graphical widgets. We used video footage from the experiment to annotate each time participants gazed at the graphical knob. The result shows that participant looked down at the mobile device 275% more for the 7mm×217mm condition in comparison with the 7mm×116mm condition. For the 1.6mm×217mm condition, the increment was of 540% in comparison with the 1.6mm×116mm condition. On the contrary, the two tangible knobs did not require visual attention to be operated.

This result suggests that, for handgrip changes –i.e., the *Medium* difficulty level from section 5.2.5.4 (page 92)– participants were able to drag the graphical knob by a single straight movement to reach the target. No tactile feedback was needed. In comparison, when the hand was relocated (i.e. the *Hard* difficulty level from section 5.2.5.4) participants needed to reacquire the knob.

5.5.6.2 Impact of Hand Movements

Handgrip changes and hand relocations proved to have a significant impact on performance. When acquiring targets over short and long distances, the performance drop around 1.2s for the non-actuated slider and 2.1s for the graphical slider. We analyzed the video footage to check the amount of times participants performed handgrip changes and hand relocations. On average, 1 handgrip change was performed at each repetition of the pointing task. In comparison, 1.5 (SD=1) and 2.5 (SD=1) hand relocations were performed with the graphical slider and with the non-actuated slider respectively. We argue that this difference is due to the thicker body of our tangible prototype. We also observed that participants were able to perform handgrip changes without stopping the operation of the slider. On the contrary, hand relocations required participants to stop operating the slider in order to reposition their hand. Moreover, we noticed that, when performing hand relocations, participants struggle to keep the balance of the prototype inside their hand. This could have negatively impacted the performance. Given these results, we suggest that handgrip changes allow for better performance not only because of the shorter distance but also because they do not require stopping the operation.

Regarding thumb-clutching, participants performed, on average, 2 and 3 clutching movements (SD=1) when acquiring targets over short and long distances respectively. However, the performance difference between short and long distances with thumb-clutching is not as significant as the performance difference with the other techniques. We speculate that this is due to the idle time caused by the motion of the actuated slider.

5.5.6.3 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, 12 out of 15 participants

waited for the knob to stop actuating before landing their thumb. To confirm this, we analyzed the mean number of times the operating hand was idle in both experiments. We found that the mean idle time's number increased 35% for the 1.6mm Width condition and 64% for the 7mm Width condition in comparison with the same conditions from the experiment in Section 5.4 (page 97). Although both conditions were not tested in the same experiment, we expected a similar performance time since both conditions present the same dimensions. 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.

5.5.6.4 Preference

Regarding the preference towards the graphical knob, we argue that this is due to the familiarity with touchscreen mobile phones. However, despite being a familiar interface for the participants, its usability score was rather low (53%). We speculate that the difficulty of reaching far targets that required hand relocations could have negatively affected the perceived usability. In this study, we used the SUS test to evaluate the usability of the techniques. Thus, we encourage future work to explore if the task –i.e. reaching close and far targets– has also an impact on the perceived usability.

Finally, participants found the actuated slider more comfortable. Since the non-actuated slider behaves as a conventional slider and SUS scores of both tangible sliders were close, we discard the assumption of a novelty effect on the actuated slider.

5.5.7 Summary of Experiment 2: Clutching with an Actuated Tangible Slider

This study does not support any of our hypotheses, contradicting the results from the experiment from section 5.4 (page 97). We explain this by the fact that participants stopped manipulating the slider during the actuation phase. This is a very important observation for the design of any system-controlled shape-changing user interface and

could enhance current taxonomies (e.g., [134]).

Regarding the interaction with the graphical slider, handgrip changes do not require visual attention but hand relocations do require visual attention for reacquiring the knob.

5.6 Experiment 3: Studying Eyes-Free Interaction with an Actuated Tangible Slider

From the previous experiment (see Section 5.5), we observed that a thin (3.9mm) conventional graphical slider outperformed a bulky (43mm) actuated tangible slider when acquiring targets in the *Medium* difficulty level from section 5.2.5.4. Since thickness on prototypes has an impact on performance [97], we redesigned the actuated prototype (see Section 5.5.1, page 107) in order to make it thinner. We aim at improving the thumb operation and thus, the performance. Moreover, we want to evaluate the interaction with our actuated solution under conditions of visual feedback and without visual feedback. We are particularly interested in observing if the motion of the actuated knob disrupts the users from being eyes-free.

From the previous experiment, we also observed that hand relocations affect the performance of conventional graphical sliders due to the required visual attention. For this experiment, we then explore an extendable graphical slider that enables thumb-clutching and thus, does not require of handgrip changes or hand relocations. We are particularly interested in observing the required visual attention of such an approach.

With this study, we aim to further explore extendable tangible sliders that enables clutching as a technique to enhance the thumb's reachability in order to facilitate one-handed interaction while supporting eyes-free interaction. The goal is to obtain enough evidence to support the *enhancing the thumb's reachability* approach as an answer for the research question introduced at the beginning of this chapter (page 81).

5.6.1 Actuated Prototype Revisited

We decided to redesign the actuated prototype in order to make it thinner and thus, closer to the shape of modern smartphones. The revisited design made use of the pinion-rack mechanism presented in Section 5.5.1 (page 107). However, in this prototype, we turned the servomotor by 90 degrees (see Figure 5-17). We also removed the fiberboard body present on the previous version of the actuated prototype. This allowed us to reduce the total thickness by 20mm.

The prototype is formed by: 1) a base composed of the slider's landmark and a FEETECH FS90R [42] continuous rotation servomotor with a pinion on its top, and 2) a piece composed of a solid block, a rack, and a flat surface that serves as the slider's knob. Its length is half (0.53) the length of the previous prototype.

As on any slider, the landmark indicates the current position of the knob. The knob is 80mm long in order to remain within the thumb's comfortable area while reaching the extremes of the slider. The knob is 10mm wide as for any conventional slider knob.

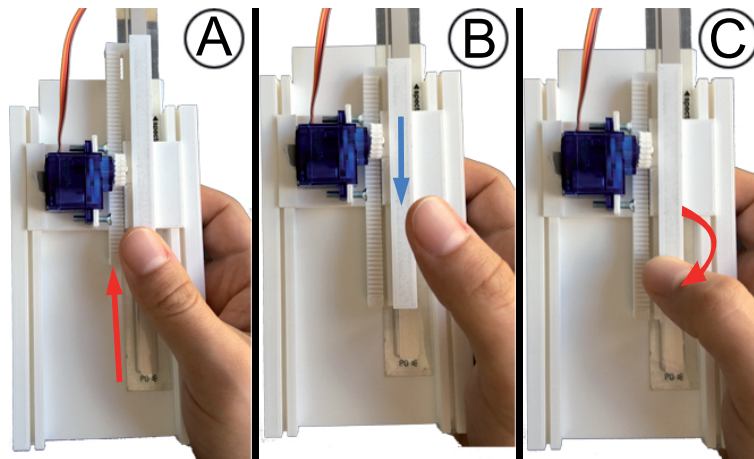


Figure 5-17: (A) The thumb pushes the knob (direction of the red arrow) until it reaches its maximum elongation. (B) The knob automatically starts to move back (direction of the blue arrow) while the thumb clutches to a comfortable position. (C) The thumb is relocated within its comfortable area and ready to continue operating.

5.6.2 Comparative Experiment

We performed the same task as in the previous experiment (section 5.5, page 107) but only with the actuated slider and an extendable graphical slider. We considered two conditions for the actuated slider in order to study eyes-free interaction with it: one condition for which the participant could look at the mobile device to get visual feedback and one condition with no possible visual feedback by covering the input device with an opaque plastic bag (see Figure 5-18). Moreover, we compared these two conditions with an extendable graphical slider. The goal is to compare the performance of clutching when manipulating: 1) an actuated tangible slider and, 2) a graphical extendable one that requires switching the visual attention from the mobile device to the screen.

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

- Tangible slider with visual feedback (**Tangible-Visual**): Participants are free to look at the input device and get visual feedback on the landmark (see Figure 5-18, A);
- Tangible slider with no visual feedback (**Tangible-Blinded**): Same as Tangible-Visual but the tangible prototype is hidden, thus preventing visual feedback as in [107]. We asked participants to operate the prototype inside an opaque plastic bag (see Figure 5-18, B);
- Graphical slider with visual feedback (**Graphical-Visual**): An extendable graphical slider that enables thumb-clutching in the same way as its tangible counterpart (see Figure 5-18, C).

We discarded the condition of 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. Participants were not able to position their thumb back into the graphical knob after clutching, arguably

due to the lack of tactile feedback. In consequence, they lost time repositioning their thumb on the screen trying to locate the graphical knob while waiting for visual feedback on the screen.



Figure 5-18: A participant performing the experiment under different conditions: (A) Tangible slider with visual feedback. (B) Tangible slider with no visual feedback. (C) Graphical slider with visual feedback.

We consider the same Distance and Width conditions from the first study for this experiment. Given these conditions, we hypothesize the following:

- H1: Eyes-free interaction with an actuated slider: manipulating an actuated slider will not result in a decrease of performance when users are not looking at the device. The automatic motion of the slider does not mean one has to look at the mobile input device;
- H2: Manipulating an actuated slider 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.

5.6.3 Apparatus and Participants

The tangible slider prototype was printed with the Ultimaker 3+ 3D printer with PLA filament. For the Graphical-Visual condition, an ASUS Zenfone 2 Laser (6-inch screen) smartphone [5] was used. We 3D printed a case for the smartphone in order to have the same thickness, equal to 20mm, between the tangible and graphical

prototypes. We made use of the same experimental software and connection setup as in the previous experiment (section 5.5) to operate the tangible prototypes. For the graphical prototype, the communication with the experimental software was done through a Wi-Fi connection.

Seventeen volunteers (between 23 and 34 years old, M=26, 11 males and 6 females) were recruited on campus.

5.6.4 Task and Procedure

For this experiment, participants performed the same task and followed the same procedure as in the previous experiment (section 5.5, page 107).

A total of 3264 measures of movement time were collected, from 17 participants \times 16 repetitions \times 3 techniques \times 2 target's widths \times 2 distances between targets. For each Technique \times Width \times Distance conditions, this resulted in 272 measures of movement time.

As in the previous experiment, we recorded the movement time to complete the task and the number of performed overshoots for each Technique. We also video recorded the hand movements and gaze of participants while operating the prototypes: we analyzed gaze diversions and thumb movements during the automatic motion of the actuated slider.

5.6.5 Results

Following Sauro *et al.* [141] recommendation, we used the geometric mean to estimate the center of the distribution of the movement time. The data was aggregated per participant and variables. A Shapiro-Wilk test revealed that we could not assume the normality of the data ($W = 0.9$, $p < 0.01$). Thus, we applied an Aligned Rank Transformation on the data [178].

A repeated measures three-way ANOVA showed a significant main effect of Technique ($F(2, 176) = 62.7$, $p < 0.0001$), Distance ($F(1, 176) = 123.7$, $p < 0.0001$) and Width ($F(1, 176) = 118.7$, $p < 0.0001$) on movement time (see Figure 5-19).

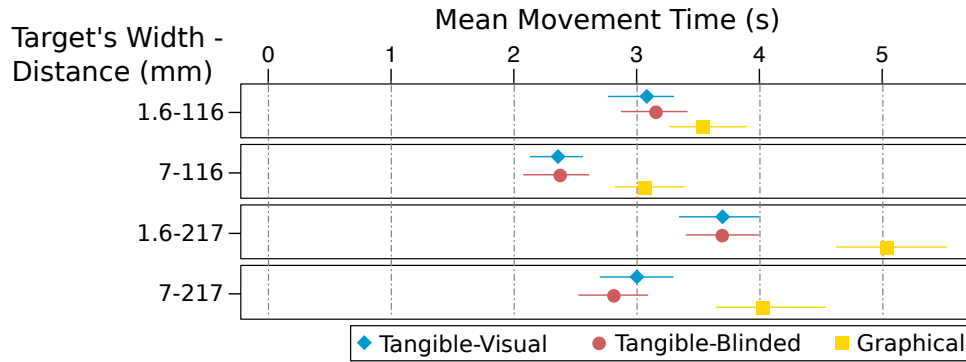


Figure 5-19: Mean movement time for the 3 Technique conditions and for the 4 possible Distance \times Width conditions (y-axis). Error bars show 95% confidence intervals.

An interaction between Technique and Distance ($F(2, 176) = 9.5, p < 0.001$) 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). A Tukey's post-hoc test revealed no significant difference between the Tangible-Visual and Tangible-Blinded conditions for both target's width conditions ($t(80) = 5.5, p > 0.05, \text{Cohen's } d = 0.4$). Similarly, for the 217mm Distance condition, the Graphical-Visual condition presented the slowest performance (+1.1s from the tangible conditions) for both target's widths. A Tukey's post-hoc test revealed no significant difference on performance between the Tangible-Visual and Tangible-Blinded conditions for both target's widths ($t(80) = 5.5, p > 0.05, \text{Cohen's } d = 0.2$). These differences are observable in Figure 5-19 where the Tangible-Visual and Tangible-Blinded conditions have similar performance times. This suggests that, when operating tangible controls, having visual feedback from the input device is not critical for performance. On the contrary, visual attention was required to operate the Graphical-Visual condition.

Regarding the number of overshoots, on average, for short distances (116mm) and small targets (1.6mm), participants overshoot 9.8 times ($SD = 0.07$) with the Tangible-Visual condition, 14.7 times ($SD = 0.14$) with the Tangible-Blinded condition, and 15 times ($SD = 0.08$) with the Graphical-Visual. For large targets (7mm), partici-

pants overshoot 6.4 times (SD=0.05) with the Tangible-Visual condition, 6.5 times (SD=0.05) with the Tangible-Blinded condition, and 7 times (SD=0.05) with the Graphical-Visual. This suggests that the tangible prototype is slightly more precise than the graphical one for small and large targets over short distances between targets.

For long distances (217mm) and small targets (1.6mm), participants overshoot 21.7 times (SD=0.17) with the Tangible-Visual condition, 21.9 times (SD=0.15) with the Tangible-Blinded condition, and 14.3 times (SD=0.07) with the Graphical-Visual. For large targets (7mm), participants overshoot 7.5 times (SD=0.06) with the Tangible-Visual condition, 10.4 times (SD=0.08) with the Tangible-Blinded condition, and 4.4 times (SD=0.03) with the Graphical-Visual. This suggests that the graphical prototype is more precise than the tangible prototype for small and large targets over long distances between targets. We speculate that the friction of

The SUS questionnaire scores indicate that participants found both the graphical slider (72.1/100, 53% after normalization [122]) and the tangible slider (71.7/100, 52.7%) equally usable. This was confirmed with ANOVA, which revealed no significant differences regarding usability between the conditions of the Knob variable ($F(1, 32) = 0.21, p > 0.05$).

5.6.6 Discussion

In this section, we discuss the observed effects that had an impact on the performance of each technique.

5.6.6.1 Eyes-free Interaction with an Actuated Tangible Slider

The Tangible-Visual condition performed equally well as the Tangible-Blinded condition for both short (116mm) and long (217mm) distances. These results suggest that the motion of the actuated slider did not prevent participants from operating in an eyes-free manner, thus supporting H1 (see Section 5.6, page 118).

On the contrary, the Graphical-Visual presented the worst performance. We ex-

plain the bad performance of the graphical slider by the number of time participants looked down to reacquire the slider’s knob. This effect has already been observed in the previous experiment when operating a conventional graphical slider (section 4 and 5.5.6, page 73 and 115 respectively). 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 required visual attention has then a stronger negative impact on performance in this experiment in comparison with the previous one from section 5.5.6. We argue that the parabolic movement of the thumb (as described in Section 2.2.2.2.1, page 22) prevented participants to operate the slider in a vertical manner. Thus, participants ended drifting their thumbs outside the graphical slider area, which we kept at 1cm wide in order to keep the same wide as the tangible prototype. We suggest that a wider graphical knob could avoid the drifting effect of the thumb and thus, stop the operation of the slider. Finally, 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 thumb-clutching. On the contrary, the tangible prototype under both visual conditions did not require visual attention to be operated.

5.6.6.2 Accuracy with an Actuated Tangible Slider

Regarding the number of overshoots, for short (116mm) distances, the Tangible-Visual was more accurate than the Tangible-Blinded and Graphical-Visual when acquiring small targets (-4.8 overshoots, SD=0.2) and large targets (-0.4 overshoots, SD=0.3). For long distances (217mm), the Graphical-Visual was more accurate than its tangible counterparts when acquiring small targets (-7.5 overshoots, SD=0.2) and large targets (-4.6 overshoots, SD=1.5). We speculate that this difference is caused by the friction which makes difficult to precisely move the tangible slider’s landmark when it is far from the thumb’s functional area. On the contrary, the graphical slider does not suffer from friction problems.

Regarding the tangible conditions, 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). This effect has been observed on a previous work on tangible sliders [107]. We speculate that participants used their peripheral vision to get visual feedback of the input device, however the measurement of the peripheral vision was out of the scope of this experiment. For future work, we want to analyze if there is a correlation between accuracy and peripheral visual feedback.

5.6.6.3 Impact of the Motion of the Actuated Tangible Slider on Performance

As in the previous experiment (see Section 5.5.6, page 115) the motion of the actuated slider disrupted the interaction. 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.

For this experiment, we expected that the thinner body of the re-designed actuated slider (-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 slider and its resulting drop in performance (+0.6s) in comparison with the large knob from the experiment in Section 5.4 (page 97), the tangible slider proved to outperform its graphical counterpart. 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 slider; supporting H2 (see Section 5.6, page 118).

For future work, we aim at evaluating the impact that the noise of the actuation has on performance. We plan to re-conduct the study but having participants operating the actuated tangible slider under a noisy condition (hearing the actuation) and silent condition (wearing noise canceling headphones).

5.6.6.4 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 [167].

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 medium fidelity since it supported good performance.

5.6.7 Summary of Experiment 3: Studying Eyes-Free Interaction with an Actuated Tangible Slider

Overall, an actuated tangible slider offers better performance for large and small targets over short distances (-0.6s) and over long distances (-1.1s) in comparison with an extendable graphical slider. This is due to the visual attention required for manipulating the graphical slider, which provoked a drop in performance. These results are in line with previous studies on tangibility and eyes-free interaction described in Section 3.1.3 (page 54).

The performance results of the tested techniques suggest that the motion of the actuated knob did not disrupt users from operating the tangible slider in an eyes-free manner. Furthermore, the stops in movement provoked by the motion of the actuated knob proved to have a smaller impact on performance than the switching of visual attention needed when operating the graphical slider.

Finally, both tangible and graphical prototypes were perceived as equally useful for the purpose of the task. We argue that a miniaturized version could increase the perceived usability of the extendable tangible slider.

5.7 Conclusion

In this chapter, we have explored two solutions for eyes-free one-handed interaction when operating sliders on mobile devices. The two solutions that we studied adopt

the two established approaches used by existing solutions, presented in Section 3.2 (page 60); these are: 1) bringing elements closer to the functional area of the thumb, and 2) enhancing the reachability of the thumb.

Our first solution aims at bringing elements closer to the comfortable functional area of the thumb. Applied to shape-changing tangible controls for eyes-free interaction, we studied the orientation and the length of the tangible sliders in order to keep them within the comfortable functional area of the thumb. From the experiment we conducted, we concluded that reducing the slider length to fit within the functional area of the thumb is not a viable solution due to the scaling effect of the motor space. On the contrary, changing the orientation of long sliders has no influence on performance, thus not supporting previous work that argue that flexion/extension movements (done on the vertical sliders) are easier than adduction/abduction movements (done with the tilted sliders) [85].

We therefore decided to explore the second approach which consists of enhancing the reachability of the thumb.

Our second solution makes use of thumb-clutching movements on an extendable tangible slider to reach targets outside the thumb's functional area while avoiding handgrip changes. For this, we first built a low-fidelity prototype of an extendable tangible slider composed of a very large tangible knob that allowed us to compare the performance of thumb-clutching movements with direct manipulation enabled by conventional tangible sliders. We then built two actuated prototypes corresponding to higher fidelity prototypes of an extendable tangible slider.

We performed three experimental studies that are summarized in Figure 5-20. Although the sample size varies between experiments (15-17 participants), we have got a decent amount of measures for each of the studied conditions (AVG= 255.5, SD=14.5). These variations were due to time constrains and the availability of participants. For future work, we would like to re-run the experiments with a bigger sample size in order to extend the generalizability of our results.

From the conducted experiments, the extendable tangible solution proved to facilitate one-handed interaction. Thumb-clutching movements are performed inside

the thumb's functional area, thus preventing handgrip changes and hand relocations. Furthermore, its tangible aspect supports eyes-free interaction. Nevertheless, the extension motion proved caused a disruption on the interaction.



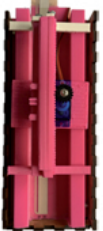




Prototypes for Thumb-clutching	Compared Techniques
	 <p data-bbox="943 533 1170 642">Handgrip Changes and Hand Relocations on a Tangible Small Knob</p>
	  <p data-bbox="943 743 1170 909">Handgrip Changes and Hand Relocations on a Tangible Small Knob and a Graphical Small Knob</p>
	 <p data-bbox="943 1031 1170 1115">Thumb-clutching on a Extendable Graphical Slider</p>

Figure 5-20: Diagram of the three experimental studies on thumb-clutching: Left column) Prototypes supporting thumb-clutching movements. Right column) Compared techniques and their corresponding prototypes.

In addition to the extendable tangible slider, our experimental study allows us to observe the three levels of difficulty of the functional area of the thumb (see Figure 5-12, page 92). The *Easy* difficulty level does not require any hand movements since the target is within the thumb's functional area. The *Medium* difficulty level requires of handgrip changes to reach targets close to the thumb's functional area. This level is present when acquiring targets over a distance that range from 80 to 116 mm. The *Hard* difficulty level requires of hand relocations in order to reach targets that are far from the thumb's functional area. This level is present when acquiring targets over a

distance of 217 mm. We want to clarify that these difficulty levels were not the focus of our studies and that the threshold of these levels can vary depending on the user's hand size and the location of the slider on the mobile device. Thus, we encourage researchers to further investigate such difficulty levels.

Furthermore, these findings allow us to answer the questions posed at the beginning of this chapter (see Section 5, page 81). For enhancing the reachability of the thumb, thumb-clutching movements proved to be a promising way to operate shape-changing tangible sliders capable of extending their length. Although a smaller length could improve performance under certain conditions (for instance, low control-display gain [24]), it could ultimately affect performance due to the scaling effect of the motor space. Such an effect is not present in an extendable slider operated in a thumb-clutching manner. We then suggest that, in order to support eyes-free interaction and facilitate one-handed interaction, shrinking the tangible slider length should be used only for low control-display gains [22]. To avoid motor space scaling, we suggest using an extendable tangible slider with thumb-clutching movements.

With these two interaction techniques, we contribute to the design space for the manipulation of mobile devices in an eyes-free one-handed manner. Indeed as shown in Tables 5.1 and 5.3 (in Sections 5.1 and 5.3, pages 82 and 94) the presented shape-changing tangible sliders define new techniques in two unexplored cells of the design space.

In this chapter we only consider interaction on the front side of the mobile device. To enhance the reachability of the thumb, we can also explore Back-of-Device interaction. This is the study that we present in the following chapter.

Chapter 6

Front/Back Side Interaction

Modern mobile devices have adopted sensors on the back side aiming to facilitate one-handed interaction, for instance, sound volume buttons [101]. In Section 3.2 of Chapter 3, we reviewed the existing literature on solutions for one-handed interaction on the back side of the mobile device. The presented solutions offer a wide range of techniques that leverage thumb interaction on the front side of the mobile device by making use of the remaining fingers on the back side. The index finger on the back has proven to cover the areas that the thumb cannot easily reach on the front side (see Section 3.2, page 60). Nevertheless, this front and back interaction technique does not support eyes-free interaction. In this chapter, we explore this solution combined with *emergeables* [136] (described in Chapter 4) to support eyes-free interaction. Thus, we rely on shape-changing tangible widgets, specifically actuated tangible sliders, to support one-handed eyes-free interaction on the front and back sides of mobile devices.

Existing interaction techniques make use of the index finger on the back side to enhance the thumb's reachability as explained in Section 3.2.2 of Chapter 3. Since Chapter 5 already presents a technique that follows the same approach for the front side of the mobile device, in this chapter we focus on addressing the following research questions:

- Is a technique that enhances the thumb's reachability more efficient when used only on the front side or on both the front and back sides of a mobile device?

- Does the motion of a shape-changing control, that operates on both front and back sides of a mobile device, disrupt interaction?

6.1 Enhancing the Reachability of the Thumb

The back side of a mobile device has been used as an auxiliary input surface to enhance the thumb's reachability by making use of the fingers placed on the back. Existing research studies (see Section 3.2.2, page 65) have proposed different interaction techniques to increase the reaching capabilities of the thumb. For instance, by supporting a different pointing technique (e.g., relative input) on the back side to leverage the pointing technique (e.g., absolute input) on the front side [159, 184]. However, none of these techniques have been explored for the manipulation of sliders in an eyes-free one-handed manner.

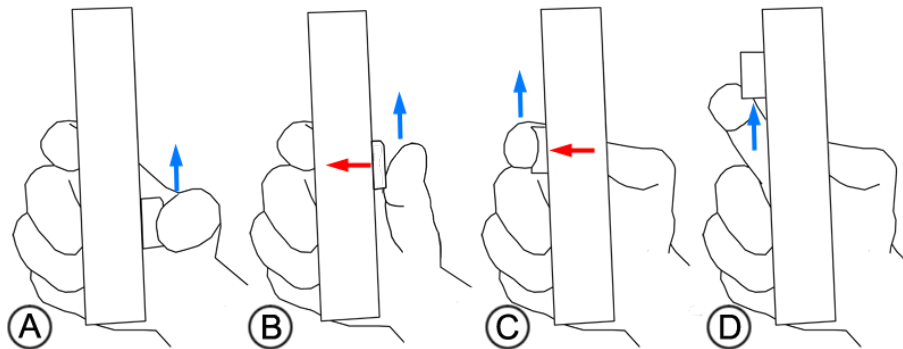


Figure 6-1: Dual-side tangible slider: Front to back actuation of a tangible slider's knob. (A) the user begins to slide the knob (direction of the blue arrow); (B) when reaching the thumb's maximum elongation, the knob automatically begins to morph into the device (direction of the red arrow); (C) the knob emerges on the back of the device so that (D) the user can continue to control the knob with the index finger.

Based on the *emergeables* concept [136] (described in Chapter 4) of mobile devices capable of morphing out tangible controls from their surfaces for eyes-free interaction, we present a shape-changing tangible slider capable of morphing-in/-out of the front and back sides. The slider's knob morphs out from the front side to allow operation with the thumb. When reaching the limits of the thumb's functional area, the slider's

knob starts to morph in the front side and morph out from the back side of the device (see Figure 6-1). This allows the user to continue the manipulation of the knob with the index finger beyond the thumb’s functional area (*Easy* difficulty level from section 5.2.5.4, page 92), without the need for changing the handgrip. Moreover, the tangible aspect of the slider allows operation without looking at the device. In Table 6.1, this technique, namely the dual-side tangible slider, is positioned in our design space of Chapter 3.


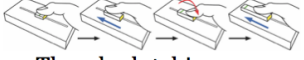
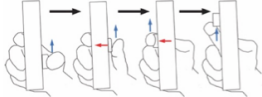
	Bringing elements closer to the thumb			Enhancing the thumb’s reachability		
	Front	Back	Lateral	Front	Back	Lateral
In-air						
Touch-based						
Tangible	 <p>Changing the orientation and length of tangible sliders</p>			 <p>Thumb-clutching on a extendable tangible slider</p>		
				 <p>Dual-side tangible slider (Front and back)</p>		

Table 6.1: The dual-side tangible slider positioned in the design space for eyes-free one-handed interaction on mobile devices: Enhancing the thumb’s reachability (x-axis); Tangible interaction (y-axis); Front and back sides (z-axis).

We present three main insights regarding our dual-side (front and back) interaction technique:

- A performance evaluation on different types of shape transitions of the slider’s knob between the front and back sides with an actuated prototype. No difference in performance is present between a gradual transition and an almost instantaneous transition. For the design of the dual-side slider prototype, we then select the instantaneous transition of the knob between the front and back sides.

In order to study the selection of targets with the designed dual-side tangible slider, we consider two of the three levels of difficulty identified in Section 5.2.5.4

of Chapter 5: an *Easy* difficulty level defines the area in which targets are directly reached by the thumb without handgrip changes; and a *Medium* difficulty level defines the area in which handgrip changes are required to reach targets and do have a negative impact on performance. We focus on the *Medium* level of difficulty and evaluate two extreme cases within this level:

- A performance evaluation when reaching targets far from the *Easy* difficulty level but still in the *Medium* difficulty level as defined in Section 5.2.5.4. While supporting a stable handgrip, the dual-side tangible slider outperforms (-0.17s) a conventional slider, and the thumb-clutching technique of Chapter 5 (-0.83s).
- A performance evaluation when reaching targets close to the *Easy* difficulty level but still in the *Medium* difficulty level from section 5.2.5.4. Although a conventional tangible slider performs slightly faster (-0.2s), the dual-side tangible slider supports a stable handgrip.

In the following sections, we describe the design and the implementation of the dual-side tangible slider prototype. We then describe three complementary experiments performed with the prototype to study eyes-free one-handed interaction with the dual-side tangible slider.

6.2 Dual-side Tangible Slider Prototype

6.2.1 Design

The functioning of the actuated slider is as follows (see Figure 6-1): the slider's knob protrudes from the front side of the mobile device; the user can then operate the knob on the front side with her/his thumb. When reaching the thumb's maximum elongation, the knob automatically begins to morph into the device and emerges on the back side. The user can then continue to control the knob with her/his index finger. The dual-side tangible slider starts actuating its knob when the user reaches the borders of the functional area of her/his thumb, i.e., the *Easy* difficulty level as

defined in Section 5.2.5.4. We focus on an indirectly controlled actuation as defined in Rasmussen *et al.*'s taxonomy [135]. We discarded system controlled and negotiated actuation, as we want to actuate the knob only when the user operates the slider and reaches the borders of the functional area of her/his thumb. We did not consider the case of directly controlled actuation to avoid stopping the operation of the slider in order to manually start the actuation.

The prototype is made of a long slider (100mm). This design does not only offer better performance (as explained in Section 5.2, page 84) but also fits within modern mobile phone sizes, e.g., the iPhone X has a height of 143mm. We placed the 100mm-slider 25mm away from the right edge of the prototype since it provides comfortable thumb operation on the front side as well as a comfortable index finger operation on the upper half back side (see Section 3.2, page 60). We envision that *Emergeable* sliders can emerge at this location preferably. Such a handgrip, in which the index finger covers the upper half back side of the mobile device, is not only efficient for Back- of-Device interaction but also a commonly observed single-handed grip (see Section 3.2).

6.2.2 Implementation

The built actuated slider is formed by: 1) a base, attached to a 100mm Bourns PTB0143-2010BPB103 slider [19], that is composed of a FEETECH FS90R continuous rotation servomotor [42] with a pinion on its top, and 2) a knob, composed of a solid block with a rack on its left side (see Figure 6-2, A).

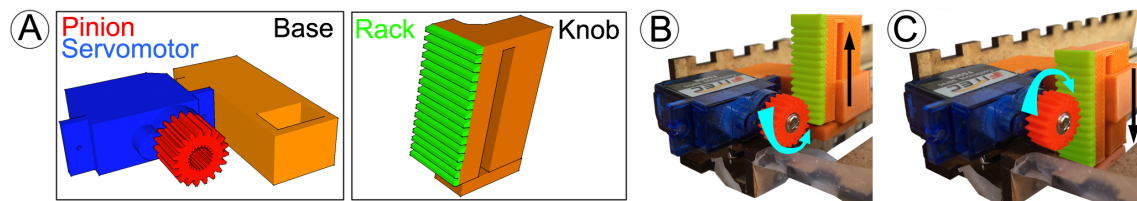


Figure 6-2: (A) Schematic of the pinion-rack mechanism powered by the servomotor. (B-C) The rotational movement of the servomotor (direction of the blue arrow) is transferred to a bidirectional movement (direction of the black arrow) of the knob.

The pinion-rack mechanism transforms the rotational movement of the servomotor into a bidirectional movement perpendicular to the slider's axis. This simulates that the knob is morphing out/in the surface according to its current position (see Figure 6-2, B-C). The knob moves from one side to the other in a single, almost instantaneous movement (250ms). The knob is then fully hidden on one side when manipulated on the opposite side of the prototype. The pinion-rack mechanism also prevents the knob from being accidentally pushed from one side to the other.

The prototype has the following dimensions (see Figure 6-3): 130mm (height), 66mm (long), and 20mm (thick). The knob has a width of 13mm and a length of 20mm, similar to any conventional slider knob.

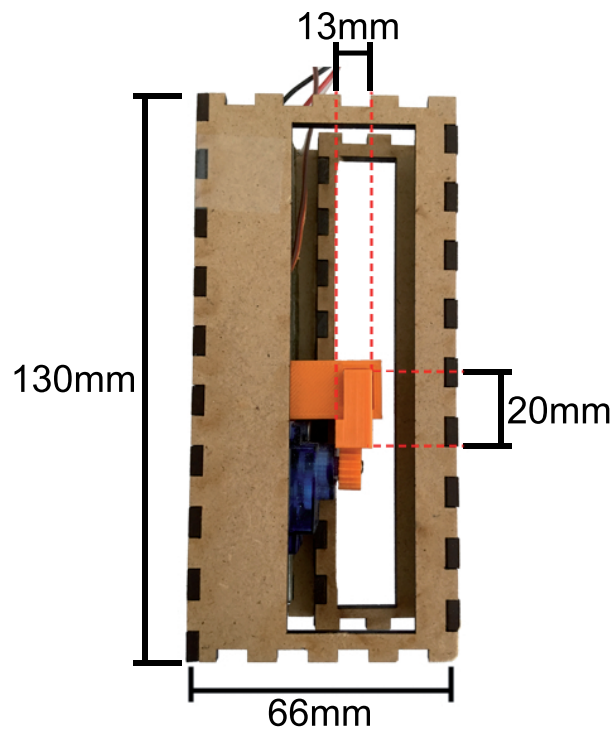


Figure 6-3: Front view of the designed dual-side actuated tangible slider prototype.

6.3 Experiment 1: Actuation of the Knob

The first experiment aims to investigate the design of the actuation of the knob of our prototype. Our motivation is to define a knob's shape transition that supports a smooth operation between front and back sides. Shape transition is a key element when designing controls that automatically change shape while being manipulated. Indeed, 1) shape transitions could be disturbing for the users [46] since they do not directly initiate the actuation and thus, could disrupt interaction; and 2) since visual feedback is limited, the shape transition could guide the users to switch from Front-to Back-of-Device interaction. Such guiding is also called interaction by invitation by Nørgaard *et al.* [121], and dynamic physical affordances by Follmer *et al.* [46]. We particularly focus on the impact of transition on performance, user's perception and preference. For the two last ones, we collected subjective qualitative feedback through a post-experiment survey.

Following a within-subject design, we evaluate three different types of shape transitions:

- **One-step:** the knob moves from one side to the other in a single, instantaneous movement (see Figure 6-4, A). The transition happens when the knob reaches a threshold of 56mm from the bottom of the slider. To define the threshold, we computed the mean thumb's functional area from participants (see Section 6.3.1, page 139).
- **Two-steps:** the knob actuates halfway through when a first threshold is reached and finishes the actuation movement when a second threshold is reached (see Figure 6-4, B). The one-step transition threshold is used as the second threshold in this transition. The first threshold is set at 28mm below the second threshold. We explore two thresholds in order to observe if a pre-transition movement (first threshold) helps participants to be ready for changing manipulation from front to back.
- **Four-steps:** the knob does three pre-transition movements before reaching a

threshold that completes the transition from one side to the other (see Figure 6-4, C). This threshold is based on the one-step transition threshold. Pre-transitions happen at 14mm from each other and from the threshold. Our motivation for this, as with the two-steps transition, is to further explore the fluidity of the transition and observe its impact on changing manipulation from front to back.

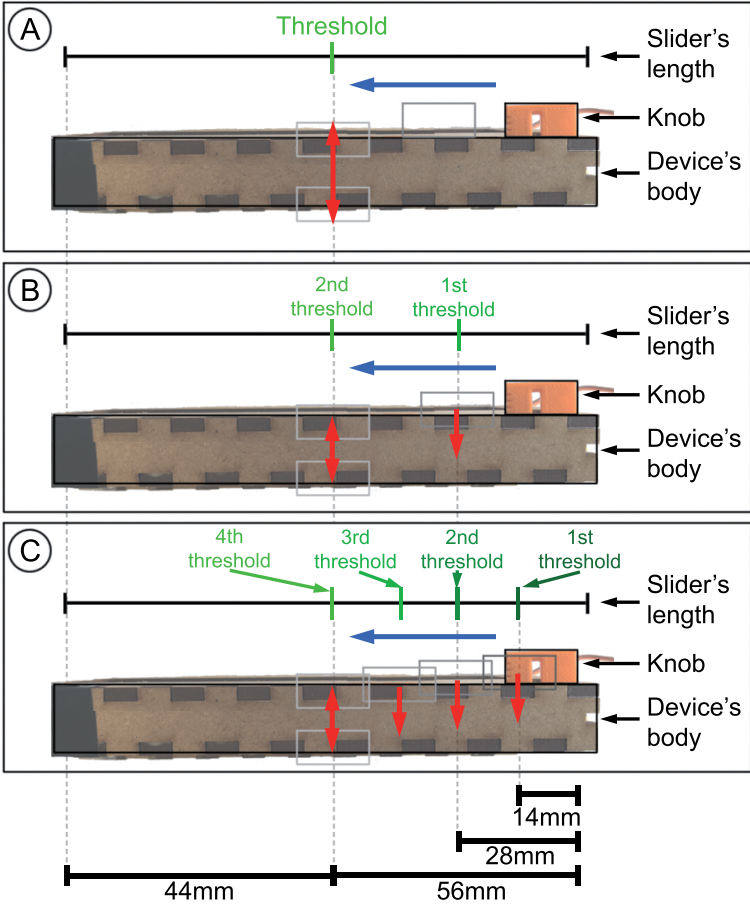


Figure 6-4: Schematic of the Transition variable conditions. When the slider’s knob is operated (direction of the blue arrow), it starts morphing inwards (single-headed red arrow) until it morphs out of the back side (double-headed red arrow).

We choose to focus on linear transitions since they provide a clear feedback about state change [163], in our case, modality change (front and back). We assume that pre-transition movements present in the two-steps and four-steps transitions will serve

as a “warning” and thus, participants will be more prepared to change manipulation from front to back. This could have an impact on pointing performance and user’s perception. On the contrary, we expect the one-step transition to suffer from this lack of feedforward. This effect of influencing a user’s behavior through an indirectly controlled actuation of a tangible control has been already observed (e.g., a button moves, when users approach it, in order to denote an active state) [163]. In this study, we are interested in observing if this effect holds during manipulation and if it helps to improve performance. For this reason, we opted for a *system controlled* transition instead of a *directly controlled* one, as defined by Rasmussen *et al.* [135]. In addition, we wanted to avoid participants stopping the operation of the slider in order to manually start the actuation.

Given our assumptions we hypothesize that the four-steps transition will have the best performance, followed by the two-steps transition.

6.3.1 Apparatus and Participants

In order to communicate with the experimental software, the prototype is connected to two Arduino Mega 2560 boards. One board is used to capture the values from the slider and the other to control the servomotor. The boards are connected via a USB cable to a 15-inch MacBook Pro laptop running the experimental software, which was displayed on a 27-inch Thunderbolt screen. The Thunderbolt display has a 2560×1440 resolution with 109 pixels per inch.

Twelve volunteers (between 25 and 34 years old, M=27, 9 males and 3 females) were recruited on campus and did not get any compensation for participating. All the participants were smartphone users. The average measured distance between participants’ thumb and index finger with the open hand was 164mm. The average measured index finger’s length was 80mm. By applying the predictive model described in Section 2.2.2.2.1 of Chapter 2 (page 22) with these values, we set the transition threshold for the transition conditions at 57mm from the bottom of the slider.

6.3.2 Task

The study requires participants to perform a distant pointing task. As explained in the previous experiments of Chapter 5 (see Sections 5.2, 5.4, 5.5 and 5.6, pages 84, 97, 107 and 118 respectively), this abstract task is representative of real life tasks in which the user needs to adjust a distant parameter without looking at the input device, e.g., filtering data displayed on a distant screen.

We applied the same task (i.e. pointing task on targets displayed on a distant screen without looking at the device in hand) as in the experiments from Chapter 5. However, we applied the following values for this experiment:

- The displayed graphical slider has a length of 100mm, exactly the same length of the slider of the dual-side tangible slider prototype. This defines a Control-Display (CD) gain of 1 which is common on mobile devices tasks (e.g., adjusting the volume on a smartphone).
- The distance between targets is 80mm, which proved to force handgrip changes (see Section 5.2, page 84). Each target has a width of 3mm, defining an index of difficulty (ID) of 4.7, as computed in [148]. The chosen ID defined a task that is not too difficult to perform [148].

The task has to be successfully finished. To validate their task, we asked participants to maintain the cursor within the target area for 1 second. This mechanism avoids any additional error-prone actions to validate the pointing [166]. Before analyzing the data, the extra second for validation was subtracted from movement time.

6.3.3 Procedure

As explained in the previous experiments of Chapter 5 (see Sections 5.2, 5.4, 5.5 and 5.6), participants sat in front of a screen displaying the experimental task. We let participants perform the task seated to avoid fatigue throughout the experiment, which lasted, on average, 50 minutes. For both actuated Technique conditions, participants were asked to find and keep a single comfortable handgrip that allows them

to operate the prototype with the index finger and the thumb throughout the trials. Moreover, participants were asked to perform the task as fast and precise as possible.

The task was performed in three blocks, one per Transition condition. The presentation order of the transitions was counterbalanced across participants. Each block was divided into 4 sub-blocks in which 17 repetitions of the pointing task were performed. This design allowed us to prevent fatigue by providing a break between sub-blocks.

The first repetition was not considered in the analysis of the data: by doing so, we avoided having results affected by the knob's position from the previous sub-block.

A total of 2304 measures of movements were collected, from 12 participants \times 64 repetitions (16 repetitions per sub-block) \times 3 transitions. For each Transition condition, this resulted in 768 measures of movement time.

6.3.4 Measures

To determine the impact of different transition types on performance time, we recorded the movement time from the beginning of each task until the validation of the target area. In addition, during the experiment, the hands of the participants were video-recorded. This allowed us to study their hand movements during the shape-changing phase of the slider and to verify that no handgrip change was present.

Finally, a post-experiment survey was designed to collect subjective qualitative data about the participants' perception during interaction and preference regarding the Transition conditions. The survey was composed of three items:

1. Did you find distracting the transitions during manipulation?
2. Did you perceive the pre-transition movements as helpful for changing operation between front and back sides?
3. Which Transition condition do you prefer the most?

6.3.5 Results

Following Sauro *et al.* [141] recommendation, we used the geometric mean to estimate the center of the distribution of the movement time. Trials were aggregated per participant and transition. A Shapiro-Wilk test revealed that we could assume the normality of the data ($W = 0.9$, $p > 0.05$), and this allowed us to run repeated measures one-way ANOVA.

The ANOVA shows that Transition ($F(2, 141) = 0.22$, $p > 0.05$) had no significant impact on movement time. On average, the one-step and two-steps conditions presented a movement time of 1.63s while the four-steps condition presented a movement time of 1.59s (see Figure 6-5).

No significant effect for the sub-blocks was found ($F(3, 140) = 0.58$, $p > 0.05$), indicating that no learning effect or fatigue were present.

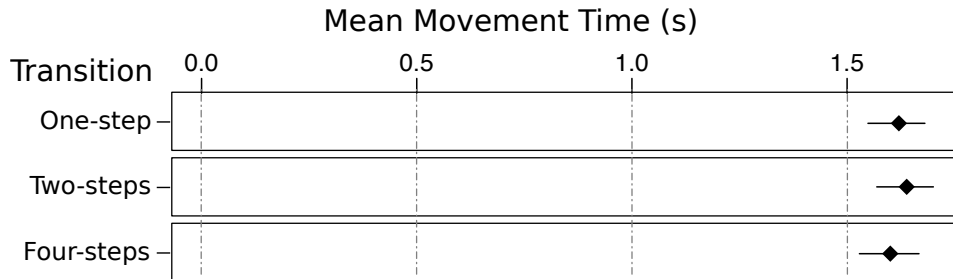


Figure 6-5: Mean movement time for the Transition conditions. Error bars show 95% confidence interval.

By using video footage, we confirmed that no handgrip change occurred while operating the prototype. The participants all maintained a stable handgrip of the device.

Finally, the post-experiment questionnaire revealed that: 1) 10 out of 12 participants found that the transition movements did not distract them from performing the task. 2) 10 out of 12 participants found the transition useful to change operation between front and back. 3) A preference towards the one-step transition (8/12), followed by the two-steps transition (4/12).

6.3.6 Discussion

Our results show no significant difference between the Transition conditions, thus discarding our initial hypothesis (i.e. a transition with several steps would perform better). From the participants' comments, the difference between Transition conditions was subtle but still perceivable. Each pre-transition movement took 125ms for the two-steps condition and 65ms for four-steps condition. We argue that with faster actuators, the perception of the pre-transition movements could be more accentuated.

6.3.6.1 Actuation During Manipulation Is Not Distracting

Video footage revealed that participants were able to continue operating the slider while the knob started transitioning from one side to the other. Furthermore, we asked participants if they found transitions distracting during manipulation. 10 out of 12 participants answered negatively. This suggests that the “morphing-in” and “morphing-out” actuation motions of the knob are compatible with the continuous manipulation of the slider.

6.3.6.2 Actuation: Guidance and Preference

10 out of 12 participants stated that the transition movements, from the two- and four-steps conditions, helped them to be ready to change operation from front to back. For example, “*The movements were like an alert to change between fingers*”; and, “*It felt like it was inviting me to change from one finger to the other*”. Although we could not support our hypothesis on performance time, this result supports previous studies on actuation for guiding participants towards a targeted behavior [46, 121].

Although participants found the two- and four-steps conditions as persuasive, they selected the one-step transition condition as their favorite one. Participants commented that it was easier to understand when to change operation between front and back with the one-step transition in comparison with the other conditions. These subjective results prove that participants were able to perceive the difference between the Transition conditions.

6.3.7 Summary of Experiment 1: Actuation of the Knob

Overall, the tested transitions do not present a performance difference between them. However, actuation during manipulation was perceived useful to prepare the user to change operation (between front and back) and was not found distracting. Furthermore, simple shape transitions (one-step transition) are better perceived. These results give a first insight of the impact of continuous actuation while manipulating a slider.

With no difference in performance, we consequently select the one-step condition as the transition for our dual-side actuated tangible slider in the following comparative experiments.

6.4 Experiment 2: Acquiring Far Targets

The goal of the second experiment with the dual-side tangible slider is to compare the performance between dual-side interaction (between front and back), handgrip changes, and thumb-clutching when acquiring targets far from the thumb’s functional area –this is, the *Easy* difficulty level as defined in Section 5.2.5.4 (page 92). For this, we compare the dual-side tangible slider with: 1) a conventional tangible slider that requires handgrip changes and 2) the actuated tangible slider that supports thumb-clutching on the front side (section 5.6, page 118). The three techniques are based on tangible sliders to support eyes-free interaction. We discard the non-actuated version of a dual-side tangible slider (with two knobs, one on each side), as it requires handgrip changes to allow the knob on the back to move freely. The experiment then follows a within-subject design with one independent variable (*Technique*), which is composed of the following conditions:

- **Dual-side interaction:** for this condition we make use of the prototype presented in the previous study (section 6.2) with a one-step shape transition. This technique allows operation with the index finger on the back of the device for targets outside the thumb’s functional area.

- **Handgrip changes:** for this condition we make use of a non-actuated tangible slider that requires handgrip changes (see Section 5.4, page 97) to reach targets outside the thumb’s functional area.
- **Thumb-clutching:** for this condition we make use of the extendable tangible slider presented in Section 5.6 (page 118), which offers eyes-free interaction and a stable handgrip. With this tangible slider, when the thumb reaches the limit of its functional area, the users can clutch, as the knob is actuated and moves back into the functional area after reaching the limit. This enables users to reach distant targets without leaving the thumb’s functional area.

We hypothesize the following:

H1: The dual-side interaction technique will outperform the handgrip changes and thumb-clutching techniques. We hypothesize that dual-side interaction (between front and back) requires less time than changing the handgrip and thumb-clutching.

H2: The handgrip changes technique will outperform the thumb-clutching technique. We hypothesize that changing the handgrip requires less time than thumb-clutching.

6.4.1 Apparatus and Participants

For the dual-side interaction condition, we use the prototype from the study in Section 6.2 (see Figure 6-6, A). For the thumb-clutching condition, we use the prototype from section 5.6 (see Figure 6-6, B). These two actuated prototypes present an actuation time of 250ms and 600ms for the dual-side interaction and thumb-clutching conditions respectively. This difference does not impact performance of the thumb-clutching technique since the user can land her/his thumb when clutching at any time during the actuation of the knob.

For the handgrip changes condition, we use the conventional tangible slider from section 5.4, see Figure 6-6, C).

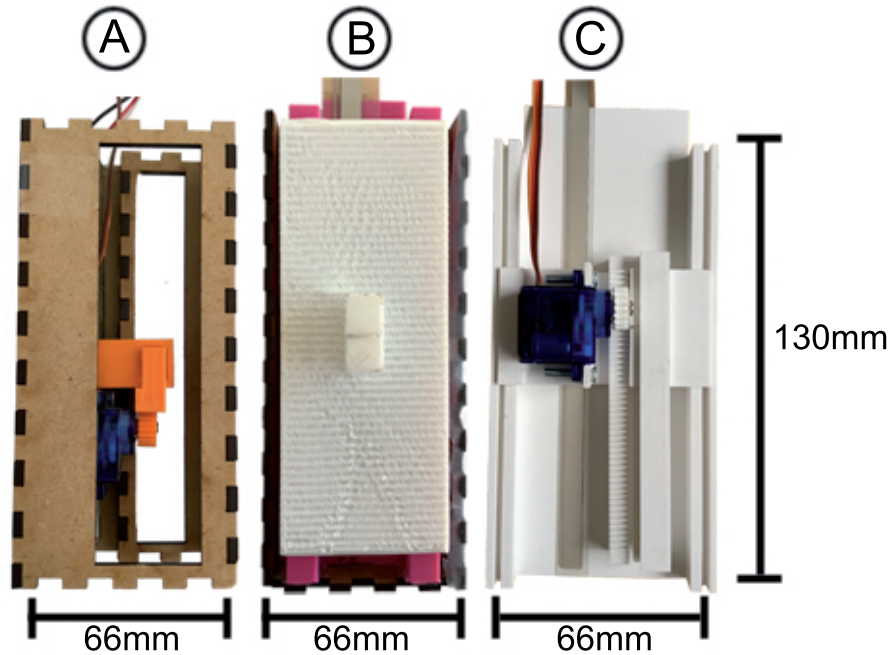


Figure 6-6: Dimensions of: A) the dual-side interaction technique prototype. B) The thumb-clutching technique prototype (as in section 5.6). C) The prototype for the handgrip changes technique.

The three prototypes have the same operational range equal to 10cm. The weights of the hand-held prototypes are: 97 grams, 108 grams and 128 grams for the handgrip changes, dual-side interaction and thumb-clutching conditions respectively. For comparison, the iPhone 6's weight is 129 grams. Although, the three prototypes differ in width, they all provided exactly the same distance between the knob and the right border of the prototype. This is necessary as all the participants were right-handed.

We use of the same connection setup between the prototypes and the distant screen as in the previous study.

Twelve volunteers (between 22 and 34 years old, M=28, 8 males and 4 females) were recruited on campus. All of the participants were right-handed. The average distance between participants' thumb and index finger and the average index finger's length were 166mm and 81mm respectively. By applying the predictive model described in Section 2.2.2.2.2.1 of Chapter 2 with these values, we set the transition threshold at 57mm from the bottom of the slider for the dual-side interaction and

thumb-clutching techniques.

6.4.2 Task and Procedure

For this experiment, participants performed the same task and followed the same procedure as in the previous experiment from section 6.3 (page 137).

For the dual-side interaction condition, participants were asked to use the slider's knob in the front only within their thumb's functional area. When the thumb was not able to reach an area, they were asked to use the knob on the back with their index finger. For the thumb-clutching condition, participants were asked to clutch with their thumb when the thumb's maximum elongation was reached. For the handgrip changes condition participants were asked to always use the thumb to operate the slider.

For both actuated Technique conditions, participants were asked to keep a single comfortable handgrip to operate the prototypes (see Figures 6-7, A-C). However, for the conventional slider, participants had no option but to change the handgrip in order to operate the prototype (see Figure 6-7, B).

Before each Technique condition was experimentally tested, a training session was performed. The training consisted of the same task as the experiment, however, with an infinite number of pointing tasks. Participants kept training with each technique until their performance time stabilized and did not vary within a range of 0.4s along 16 consecutive repetitions of the pointing task. On average, participants performed 150 repetitions of the pointing task in 10 minutes of training session. After the training phase, the trials started.

A total of 2304 measures of movement were collected, from 12 participants \times 64 repetitions (16 repetitions per sub-block) \times 3 techniques. For each Technique condition, this resulted in 768 measures of movement time. Our objective is to determine the impact on performance of the different techniques. To this end, as in the first experiment, we recorded the movement time from the beginning of each task until the validation of the target area. In addition, we recorded the number of performed overshoots (i.e. passing over a target – entering and leaving the target area) in order

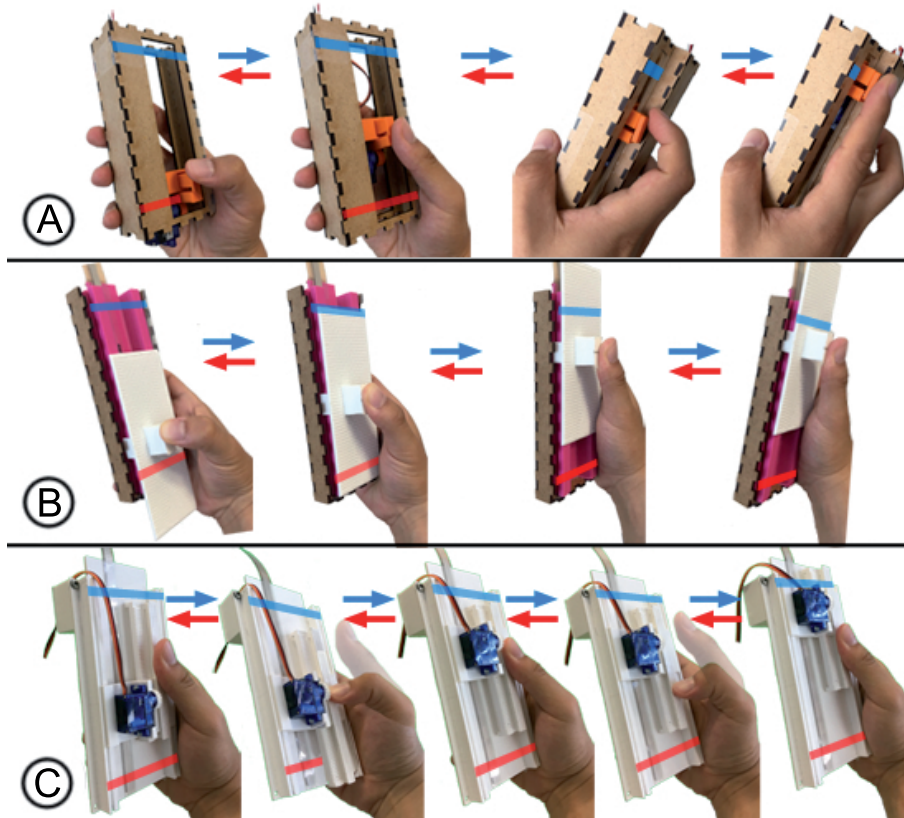


Figure 6-7: Task performed with the 3 Technique conditions. (A) dual-side interaction technique, (B) handgrip changes technique, and (C) thumb-clutching technique. The successive targets are represented in blue and red.

to study the accuracy of the techniques (as done in [166]). Moreover, during the experiment the hands of the participants were video-recorded at 29.98 FPS. This allowed us to study their hand movements and to verify that no handgrip change was present with the actuated prototypes.

6.4.3 Results

Following Sauro *et al.* [141] recommendation, we used the geometric mean to estimate the center of the distribution of the movement time. Trials were aggregated per participant and technique. A Shapiro-Wilk test revealed that we could not assume the normality of the data ($W = 0.9$, $p < 0.05$). Thus, we applied an Aligned Rank Transformation on the data [178] and then ran a repeated measures ANOVA.

The Technique ($F(2, 121) = 153.6, p < 0.0001$) had a significant impact on movement time. On average, the dual-side interaction technique presented a movement time of 1.61s while the handgrip changes and thumb-clutching techniques presented a movement time of 1.78s and 2.44s respectively (see Figure 6-8). To confirm these time differences, we ran subsequent Tukey post-hoc tests with pairwise comparisons. The test revealed significant difference ($p < 0.001$) between the dual-side interaction and the other two techniques, and between the handgrip changes and thumb-clutching techniques ($p < 0.0001$). Hence, dual-side interaction is fastest technique, followed by handgrip changes and the thumb-clutching technique is the slowest.

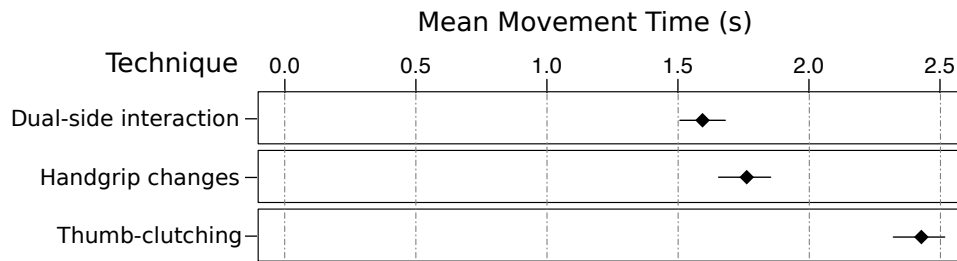


Figure 6-8: Mean movement time for the Technique conditions. Error bars show 95% confidence interval.

No significant effect for the sub-blocks was found ($F(3, 121) = 2.1, p > 0.05$), indicating that no learning effect or fatigue was present.

Regarding the number of overshoots, on average, participants overshoot 2.7 times ($SD=0.4$) with the dual-side interaction technique, 3.8 times ($SD=0.7$) with the handgrip changes technique, and 6.8 times ($SD=0.9$) with the thumb-clutching technique. This suggests that the dual-side interaction technique provides an accuracy level 29% more precise than the handgrip changes technique and 60% than the thumb-clutching technique.

Based upon the video footage from the experiment, one handgrip change was required at each repetition of the task (see Figure 6-7, B), giving a total of 64 handgrip changes for the handgrip changes technique. And no handgrip change has been observed for the dual-side interaction (see Figure 6-7, A) and thumb-clutching (see

Figure 6-7, C) techniques. This is important since a study from Eardley *et al.* (see Section 2.2.2.3, page 62) found a correlation between handgrip changes and the perception of security (i.e. risk of device being dropped) for different body postures. In the study, participants rated the likelihood of dropping the mobile phone from the operating hand/s at different body postures. When standing, 30 handgrip changes were graded 4 in a 7pt likert scale regarding the likelihood of dropping the mobile device, and when lying 100 handgrip changes were graded 1.6 (being 1 the least secure).

6.4.4 Discussion

Results show that the dual-side interaction technique outperformed the handgrip changes technique (-0.17s) and the thumb-clutching technique (-0.83s), thus supporting H1. The handgrip changes technique outperformed (-0.66s) the thumb-clutching technique, thus supporting H2. We further discuss the two hypotheses in the light of the results.

6.4.4.1 Dual-side Interaction vs. Handgrip Changes

Participants lose time when changing operation between front and back with the dual-side interaction technique. Video footage from the experiment revealed that, when changing operation from front to back, the slider's knob was not used for 3.6 frames - approximately 120ms (SD=59ms). On the contrary, handgrip changes happened while the participants were operating the slider. Thus, handgrip changes did not imply an idle time in which the thumb was not operative. This suggests that the process of changing the handgrip directly affects the performance while operating the slider. In consequence, handgrip changes provoke a slower performance in comparison with dual-side interaction.

We observed that, when participant performed a change in the handgrip, the prototype's orientation greatly changed (see Figure 6-9). We argue that handgrip changes require positioning the fingers in a way that could be uncomfortable and non-optimal for manipulation, thus slowing down the performance. These results go

in line with the results of our previous experiments on handgrip changes of Chapter 5 (see Sections 5.2, 5.4 and 5.5, pages 84, 97 and 107 and respectively) and previous studies (see Section 2.2.2.3, page 25).

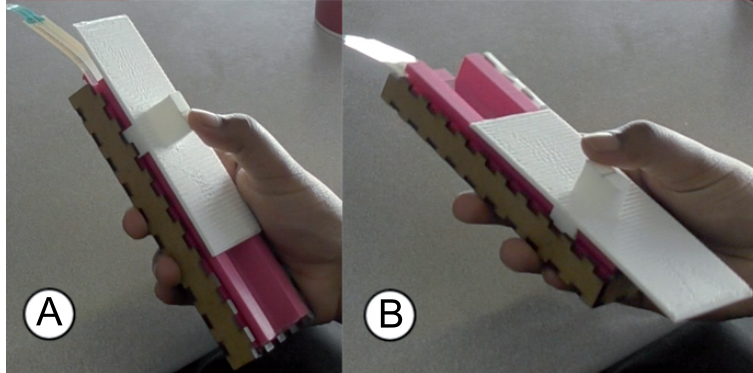


Figure 6-9: Handgrip changes required when moving the knob of a conventional tangible slider between the bottom (A) and the top (B).

6.4.4.2 Dual-side Interaction vs. Thumb-Clutching

We argue that thumb-clutching movements take more time than changing operations between front and back with the dual-side interaction technique. To verify this, we made use of video footage from the experiment. We checked the number of frames for which the slider knob was not operated when doing thumb-clutching movements. On average, the slider's knob was not used for 12.6 frames - approximately 420ms (SD=46ms) - per trial due to thumb-clutching. On average, two thumb-clutching movements were performed per trial, hence each clutching movement lasted approximately 210ms. On the contrary, changing operation between front and back was performed once per trial and the slider's knob was not used for approximately 120ms (SD=59ms). In consequence, thumb-clutching provokes a slower performance in comparison with dual-side interaction.

We speculate that the thumb-clutching idle times are related to the actuation effect previously reported in Sections 5.5.6 and 5.6.6 (pages 115 and 124 respectively). Despite being able to land the thumb at any time when using the thumb-clutching

technique, some participants waited until the actuation was close to finishing before landing the thumb.

6.4.4.3 Handgrip Changes vs. Thumb-Clutching

The performance time of the thumb-clutching technique confirms a tendency described in Section 5.4 (page 97). Indeed, thumb-clutching movements tested with a distance between targets of 217mm, outperformed handgrip changes by 0.5s (results from section 5.4). When tested with a distance of 116mm (see Section 5.4), both techniques presented similar performance time (results from section 5.4). Our results show that with a smaller distance equal to 80mm, handgrip changes outperform thumb-clutching movements. This suggests that thumb-clutching movements are faster than handgrip changes to acquire targets over long distances that are at least longer than 116mm.

6.4.5 Summary of Experiment 2: Acquiring Far Targets

Overall, dual-side interaction (between front and back) requires an idle time that has a lower impact on performance in comparison with the idle time from thumb-clutching and the hand movements needed to perform handgrip changes. The dual-side technique offers a good performance and a stable handgrip when acquiring targets far from the *Easy* difficulty level of the functional area of the thumb.

The dual-side interaction and thumb-clutching techniques require an idle time in which the slider is not manipulated. For dual-side interaction the idle time is 120ms, and for thumb-clutching the idle time is 420ms. We speculate that these idle times are correlated to the actuation time of the actuated prototypes.

Finally, the results of this experiment and a previous one (see Section 5.4) suggest that the performance of the thumb-clutching technique decreases as the distance between targets shrinks. We define a distance between targets of 116mm as the threshold in which thumb-clutching stops outperforming handgrip changes. Hence, we do not consider the thumb-clutching technique in the third experiment that involves

shorter distances than 116mm.

6.5 Experiment 3: Acquiring Close Targets

The previous experimental study (see Section 6.4, page 144) shows that the dual-side tangible slider provides good performance when acquiring targets over long distances that require handgrip changes with a conventional tangible slider –this is, the *Medium* difficulty as defined in Section 5.2.5.4 (page 92). However, it is unclear how the dual-side interaction technique affects performance when acquiring targets close to the transition threshold. In this experiment we focus on interaction when reaching targets near the borders of the thumb’s functional area, i.e., *Easy* difficulty level. For this, we compare the dual-side interaction and handgrip changes techniques from the previous experiment (section 6.4), and considered two variables: *Slider Part* and *Distance*.

The *Slider Part* variable refers to the part of the slider in which the movement of the knob is mostly performed to reach the target (see Figure 6-10). We test two conditions: bottom and top parts, respectively below and above the border of the thumb’s functional area, i.e., *Easy* difficulty level from section 5.2.5.4.

The *Distance* variable refers to the distance between targets displayed on the distant screen (see Figure 6-10). We consider four conditions: 36mm, 44mm, 50mm and 58mm. We cross the *Slider Part* and *Distance* variables as follows: Bottom-50, Bottom-58, Top-36, and Top-44. Since the *Slider Part* and *Distance* variables are not fully crossed, we consider them as a single variable that we call the *Slider Part-Distance* variable. Such a combination allow us to test the techniques for targets close to the borders of the thumb’s functional area (both inside and outside). The reason for a shorter distance on the top area of the slider is that the functional area of the index finger is smaller than the functional area of the thumb as a study by Le *et al.* shows [98].

On the one hand, the Bottom-50 and Top-36 conditions allow us to evaluate the performance of the two techniques without handgrip changes and changing operation

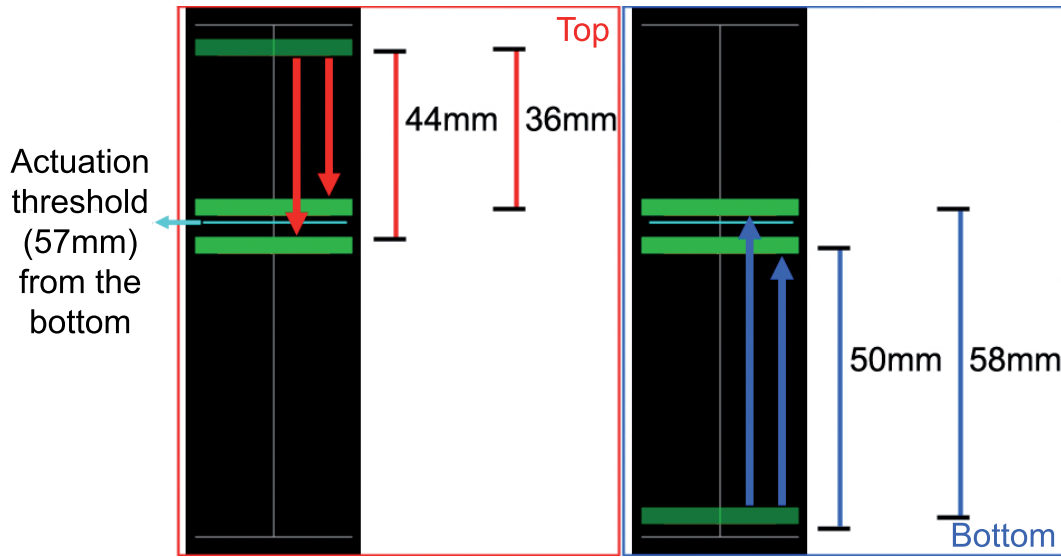


Figure 6-10: Representation of the Slider Part-Distance variable on the pointing task as displayed on a distant screen. The green rectangle represents the target area.

between front and back. Indeed, for the handgrip changes technique, participants start with a handgrip that keep the operation inside the thumb's functional area. As shown in Figure 6-11, for the dual-side interaction technique, Bottom-50 condition is performed with the thumb only while Top-36 condition with the index finger only.

On the other hand, the Bottom-58 and Top-44 conditions require handgrip changes and changing operations between front and back. For the handgrip changes technique and Bottom-58 condition, participants started with the handgrip that allows to manipulate the knob within the bottom part. They finished the task with the handgrip that allows to manipulate the knob in the top part. The following task (i.e. going down) started with the handgrip for the top part and finished with the one for the bottom part, and so on. Since they were asked to keep the thumb on top of the knob at all times, a handgrip change was required for each task. Symmetrically for the handgrip changes technique and Top-44 condition, participants started with a handgrip for the top part and finished the task with a handgrip for the bottom part. For the following task (i.e. going up), they started with a handgrip for the bottom part and finished with a handgrip for the top part. For the dual-side interaction

techniques, the changing operations between front and back are presented in Figure 6-11 for the two conditions Bottom-58 and Top-44.

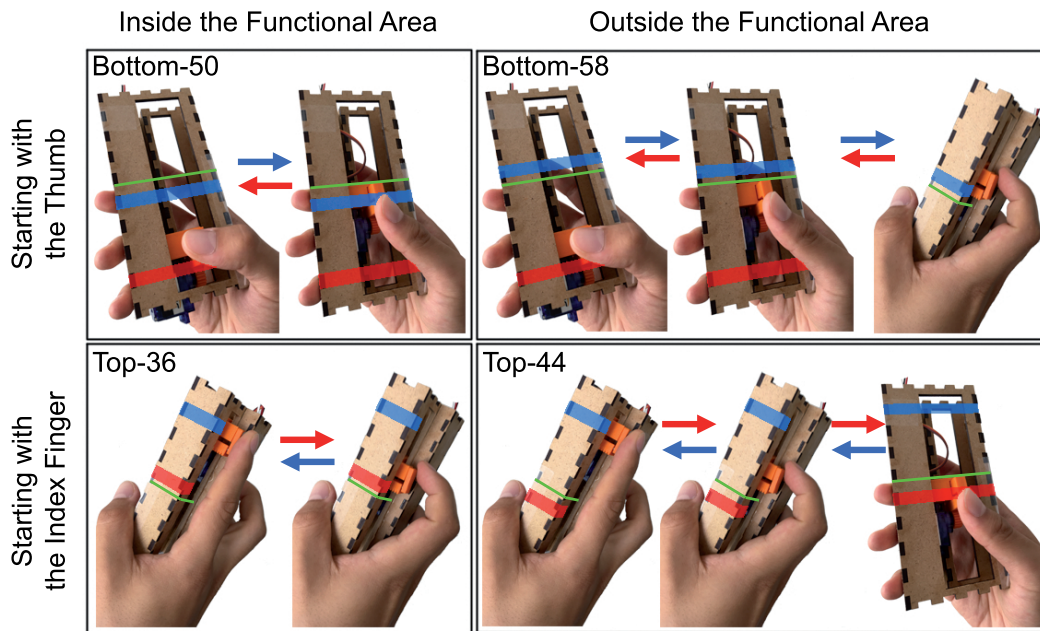


Figure 6-11: Representation of the Slider part-Distance conditions with the dual-side interaction technique. The successive targets are represented in blue and red. The green line represents the transition threshold (57mm from the bottom).

We remind the reader that, as in the previous experiment, we discard a non-actuated version of a dual-side tangible slider (with two knobs, one on each side), as it requires handgrip changes to allow the knob on the back to move freely.

For this experiment, we hypothesize the following:

- H1: The dual-side interaction and handgrip changes techniques will equally perform when reaching targets located before the transition threshold. We hypothesize that the index finger (top) and the thumb (bottom) operations perform equally well.
- H2: The handgrip changes technique will outperform the dual-side interaction technique when reaching targets located right after the transition threshold. We hypothesize that handgrip changes close to the thumb’s functional area do not

greatly change the initial handgrip.

6.5.1 Apparatus and Participants

We use the same prototypes and setup from the previous study (section 6.4).

Seventeen volunteers (between 22 and 34 years old, M=27, 11 males and 6 females) were recruited on campus. All of the participants were right-handed. 7 participants from the previous study of section 6.4 participated in this experiment. The average distance between participants' thumb and index finger and the average index finger's length were similar to the ones from the experiment in Section 6.4 (167.8mm and 81.3mm respectively). Hence, we keep the same transition threshold (57mm) for the dual-side interaction technique.

6.5.2 Task and Procedure

For this experiment, participants performed the same task and followed the same procedure as in the previous experiment (see Section 6.4, page 144). The presentation order of the Slider Part-Distance variable was randomized.

For each Slider Part-Distance condition, 17 repetitions of the pointing task were performed. The first repetition was not considered in the analysis: by doing so, we avoided having results affected by the knob's position from the previous repetition.

A total of 2176 measures of movement time were collected, from 17 participants \times 16 repetitions \times 2 techniques \times 4 slider part-distance conditions. For each Technique \times Slider Part-Distance conditions, this resulted in 272 measures of movement time.

We recorded the movement time, the number of performed overshoots, and video recorded the participants' hands while operating the prototypes. We concluded the session by asking participants to fill in a SUS questionnaire [122] on the Technique conditions. We also asked participants about their general impression of the techniques and which technique was more comfortable to use.

6.5.3 Results

Following Sauro *et al.* [141] recommendation, we used the geometric mean to estimate the center of the distribution of the movement time. Trials were aggregated per participant, technique and the Slider Part \times Distance combination. A Shapiro-Wilk test revealed that we could not assume the normality of the data ($W = 0.9$, $p < 0.01$). Thus, we applied an Aligned Rank Transformation on the data [178] and then ran a repeated measures ANOVA.

The Technique ($F(1, 111) = 31.7$, $p < 0.0001$) and Slider Part-Distance conditions ($F(3, 111) = 11.9$, $p < 0.0001$) had a significant impact on movement time. An interaction between Technique and Slider Part-Distance ($F(3, 111) = 8.8$, $p < 0.0001$) also proved to be significant. This interaction is observable in Figure 6-12: the dual-side interaction and the handgrip changes techniques present a significant difference in performance in all conditions except with the Bottom-50 condition. To confirm the time differences between techniques, we ran subsequent Tukey's post-hoc tests. For the Bottom-58, Top-36, and Top-44 conditions, the techniques presented a significant difference between each other ($p < 0.01$). For Bottom-50, no significant difference was found between techniques ($p > 0.05$).

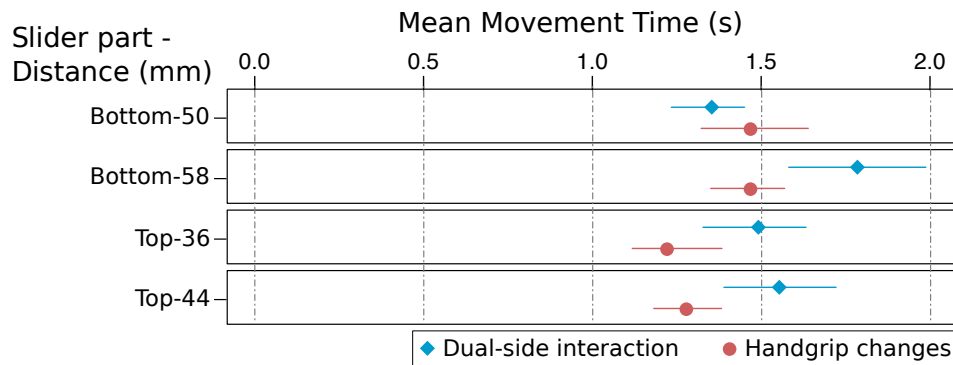


Figure 6-12: Mean movement time for the 2 Technique and 4 Slider part-Distance conditions. Error bars show 95% confidence interval.

Regarding the number of overshoots, the handgrip changes technique presents an average of 4.5 overshoots ($SD=0.6$) across all Slider Part-Distance conditions. The

dual-side interaction technique presents an average of 6.7 overshoots (SD=0.8) for the Bottom-58 and Top-36 conditions, 3.4 overshoots (SD=0.5) for Bottom-50, and 4.4 overshoots (SD=0.6) for Top-44.

As for the previous experiment, one handgrip change was required at each repetition of the task in conditions Bottom-58 and Top-44, giving a total of 32 handgrip changes for the handgrip changes technique. No handgrip change has been observed for conditions Bottom-50 and Top-36. Furthermore no handgrip change has been observed for the dual-side interaction technique for the four conditions.

ANOVA revealed that differences were significant between the conditions of the Technique ($F(1, 26) = 20, p < 0.0001$). The SUS scores indicate that participants found both the handgrip changes (83.7/100, 62% after normalization [122]) and dual-side interaction (70/100, 51% after normalization) techniques as usable. This suggests that the dual-side interaction is significantly perceived as being more usable than handgrip changes.

6.5.4 Discussion

Results show that, on average, the handgrip changes technique performed better (1.3s) than the dual-side interaction technique (1.5s), thus not supporting H1 and supporting H2.

6.5.4.1 Reaching Targets Within the Functional Area

For the Bottom-50 condition, both dual-side interaction and handgrip changes techniques presented an average movement time of 1.38s. This result was expected since, for this condition, both techniques require similar thumb operation inside the thumb's functional area –this is, the *Easy* difficulty level as defined in Section 5.2.5.4 (page 92). On the contrary, for the Top-36 condition, the difference between the dual-side interaction and the handgrip changes techniques is significant (1.5s and 1.2s respectively). We argue that this difference is due to the use of the index finger to operate the slider with the dual-side interaction technique.

For this experiment we expected that index finger operation on the back side would, at least, perform equally well as thumb operation on the front side since the previous experiment (see Section 6.4) shows that the dual-side interaction technique outperforms the handgrip changes technique. We argue that in the previous experiment (see Section 6.4) the strong impact of handgrip changes on performance prevented us to observe the slightly lower performance of the index finger movements (dual-side interaction technique) in comparison with the thumb movements (handgrip changes technique). However, result of this experiment support the work by Wobbrock *et al.* (see Section 3.2, page 81) on the performance of the index finger operations on the back versus the thumb operations on the front on a touchpad for vertical movements with ID as a continuous factor ranging from 1.32 to 4.64 bits. Moreover, for the dual-side tangible technique the number of overshoots increased by 30% for the Top-36 condition in comparison with the Bottom-50 condition.

6.5.4.2 Reaching Targets Near the Functional Area

The performance of the dual-side interaction technique was affected when the target was located close to the transition threshold (Bottom-58 and Top-44 conditions). The average movement time is 1.6s for the dual-side interaction technique and 1.3s for the handgrip changes technique. We argue that: 1) as opposed to the previous experiment (section 6.4, page 144), handgrip changes close to the thumb’s functional area are not important enough to impact performance; and 2) the inoperability of the slider caused by the actuation motion (as explained in Section 6.4.4, page 150), has an impact on performance. Again, we argue that the effect of the knob actuation was not directly observable in the previous experiment (section 6.4) because it was masked by the strong impact of handgrip changes.

6.5.4.3 Subjective Preference

Both dual-side interaction and handgrip changes techniques were perceived as usable. Furthermore, the dual-side interaction technique is not only found more comfortable to use but is also described as “interesting”, “playful”, and “natural”. This feed-

back highlights the positive perception regarding dual-side interaction with tangible interfaces.

6.5.5 Summary of Experiment 3: Acquiring Close Targets

Overall, handgrip changes proved to offer better performance than dual-side interaction at the cost of provoking uncomfortable and unsafe handgrips (see Section 2.2.2.3, page 25).

When targets are close enough that do not require changing operation between front and back with the dual-side interaction technique, the handgrip changes technique performs better for the top part of the slider. For the bottom part, both dual-side interaction and handgrip changes techniques perform equally well.

When targets are far enough to require changing operation between front and back with the dual-side interaction technique, the handgrip changes technique performs better for both top and bottom part of the slider.

Despite all this, participants had a positive perception of the dual-side interaction technique and commented that it was comfortable to use.

6.6 Conclusion

In this chapter, we have experimentally explored a solution for the eyes-free one-handed interaction problem when operating sliders on mobile devices. The solution adopts an established approach used by existing solutions (see Section 3.2.2, page 65): the index finger (positioned on the back side of the device) is used as an auxiliary input to enhance the reachability of the thumb on the front side.

Our solution shows benefits for different situations. On the one hand, for targets far from the thumb's functional area (i.e. *Medium* difficulty level from section 5.2.5.4, page 92) our solution outperforms (-0.17s) direct manipulation supported by a conventional tangible slider. On the other hand, for targets close to the *Easy* difficulty level but still in the *Medium* difficulty level, although a conventional tangible slider performs slightly faster, our solution supports a stable handgrip. Such feature could

be desired on different scenarios. For instance, mobile situations increase the hand oscillation, which could ultimately make the user drop the device (see Section 2.2.2.3, page 25). Moreover, stationary body postures (like sitting and lying down) have also shown to decrease the stability of the handgrip in comparison with a standing body posture (see Section 2.2.2.3). Finally, a dual-side interaction technique is positively perceived in terms of usability and comfort.

Furthermore, our studies also shed a light on the impact of shape transition on interaction. This is a key element when designing controls that automatically change shape while being manipulated. We observed that the actuation of the dual-side interaction technique had a lower impact on performance than the actuation of the thumb-clutching technique of the previous chapter. The two actuated solutions of chapter 5 and chapter 6 present two different parameters in terms of shape transition: the orientation and the amplitude of the actuation.

We suggest that the orientation of the shape transition is a relevant parameter to take into consideration when designing shape-changing tangible controls. We asked participants how they felt regarding the actuation of the slider of the thumb-clutching technique. Participants claimed that actuation was distracting since the slider knob actuated on the opposite direction of the thumb's movement. For example: *"...I was pushing the knob upwards and it started deforming downwards, I thought it was relocating the whole knob..."*. On the contrary, a "morphing-in/out" motion does not disrupt interaction on an actuated slider.

Evidence suggests that the amplitude of the shape transition is another relevant parameter to take into consideration. As explained in Section 6.4 of Chapter 5 and also in Section 6.4 of this chapter, participants did not manipulate the thumb-clutching technique (which required 600ms of actuation time) for 420ms. On the contrary, with the dual-side interaction technique (which required 250ms), participants did not interact for 120ms. Although we cannot conclude that these values are correlated, it provides a hint about the possible impact that the amplitude of the shape transition has on interaction.

The findings presented in this chapter allow us to answer the questions posed at

the beginning of this chapter (page 131):

- Operation of a slider with the index finger on the back side of a mobile device (to cover the unreachable area of the thumb) proves to perform better (-0.8s) than thumb-clutching movements (previous chapter) that operate only on the front side;
- the front-to-back motion of an actuated slider on a mobile device does not interrupt a dual-side interaction between the thumb on the front and the index finger on the back sides. Furthermore, participants highlighted the usefulness of such actuation design by indicating how the motion helps them change operation between the front and back sides.

With our dual-side interaction technique, we contribute to the design space for the manipulation of mobile devices in an eyes-free one-handed manner. Indeed as shown in Table 6.1 (beginning of this Chapter, page 131) the dual-side tangible slider defines a new technique in an unexplored cell of the design space.

The dual-side tangible slider concludes the Solution Space part of this thesis, dedicated to new interaction techniques for eyes-free one-handed interaction on mobile devices. The following chapter will conclude the doctoral study with a brief summary of our contributions and future perspectives.

Chapter 7

Conclusion

Mobile devices, such as smartphones and tablets, are widely used nowadays due to their multiple functionalities to help us in our everyday activities. In the context of mobile interaction, two different situations are frequently faced by users: 1) using the mobile devices while keeping the visual attention on the surroundings, and 2) being able to comfortably manipulate the mobile device with a single hand. The first situation refers to eyes-free interaction, a feature highly desired in a wide range of scenarios (e.g., manipulating the mobile device while crossing a street, walking down the stairs or while interacting with other people). The second situation refers to one-handed interaction, a feature highly desired by users when the second hand is not available (e.g., when carrying a grocery bag) or for comfort preferences. We focused on these two issues, namely, *eyes-free one-handed interaction*. This is a vast research subject and we narrowed the subject to the case of continuous controls, and particularly to interaction with sliders on mobile devices. The adjustment of continuous parameters with sliders on mobile devices is common both in professional environments (e.g., audio engineers fixing the sound volume of a venue before a concert, and scientists filtering data displayed on a wall-sized display) and domestic ones (e.g., a person at home adjusting the speaker's sound volume or the lamp's light color).

Our aim was to improve interaction with sliders on mobile devices. In this context, the research question we addressed is how to improve eyes-free one-handed interaction with a slider on a mobile device. In order to answer this question, we adopted a two-

step approach (see Figure 7-1):

1. We established a design space (first contribution) based on our review of existing techniques for eyes-free interaction and one-handed interaction. The design space is formulated along the set of characteristics that we identify for eyes-free one-handed interaction. We also describe a concept for eyes-free interaction on mobile devices called *Emergeables* [136] in order to illustrate the mobile device of the future that could support new interaction techniques for eyes-free one-handed interaction.
2. Based on our design space and the concept of *Emergeables* [136]¹, we designed three new eyes-free one-handed interaction techniques (second contribution) that we experimentally tested.

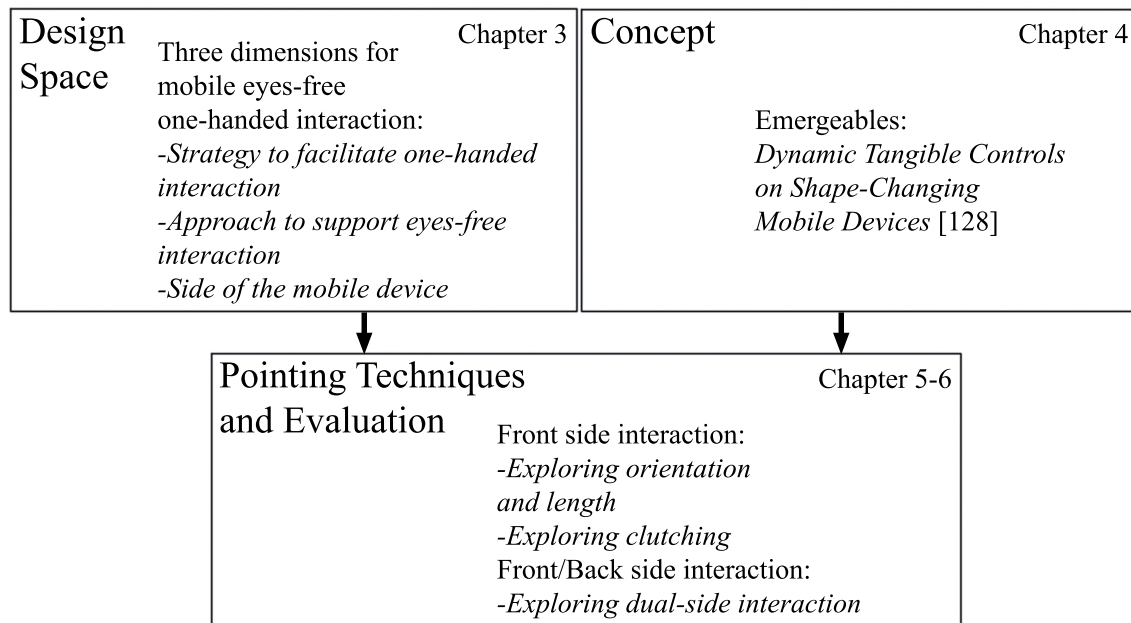


Figure 7-1: Adopted approach and summary of contributions.

Below, we will sum up our contributions. We will then present the perspectives on this work.

¹the author of this thesis was part of the research team

7.1 Contributions

We contribute to two sub-domains of HCI (see Figure 7-2): mobile interaction and shape-changing tangible interfaces.

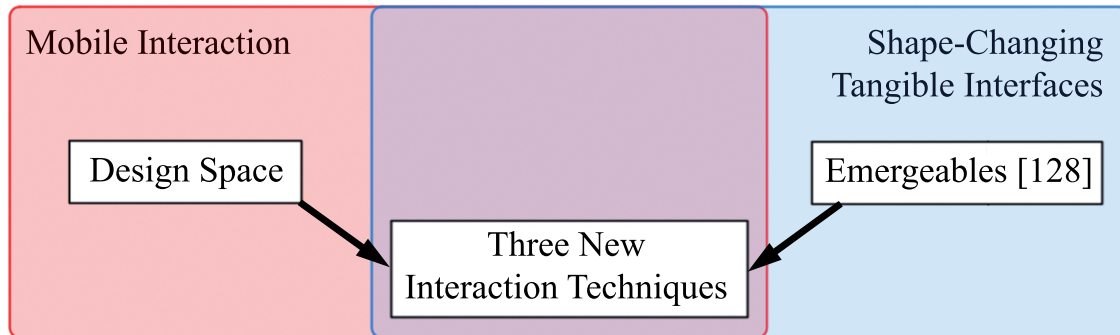


Figure 7-2: Diagram of the contributions and their corresponding HCI sub-domains.

7.1.1 Design Space

We established a design space for eyes-free one-handed interaction on mobile devices. The design space is organized around three dimensions derived from the existing work in the literature: 1) the strategy used to facilitate one-handed interaction, 2) the approach used to support eyes-free interaction, and 3) the side of the mobile device where the interaction takes place.

The first dimension refers to the *strategy used to facilitate one-handed interaction*. Two strategies are identified along this dimension:

- **Bringing elements close to the thumb’s comfortable area:** This strategy refers to techniques that focus on displacing the interface through explicit actions (e.g., tilting the device, bezel-scroll gesture, button pressed for proxy views) in order to bring unreachable areas within the thumb’s functional area;
- **Enhancing the thumb’s reach capabilities:** This strategy refers to techniques that make use of graphical widgets (e.g., magnetic sticks) or another modality (e.g., operation with the index finger on the back side of the mobile

device) that serve as an extension of the thumb to reach elements outside the thumb's functional area.

The second dimension refers to the *approach used to support eyes-free interaction*.

Three approaches are identified along this dimension:

- **In-air:** this approach relies on in-air body gestures (e.g., moving the hand up and down, rotating the foot) to support eyes-free interaction.
- **Touch-based:** this approach makes use of hand gestures, such as tapping, swiping, and tilting, to interact with mobile devices in an eyes-free manner.
- **Tangible:** this approach presents tangible elements on the surface of the mobile device to support eyes-free interaction.

The third dimension refers to the *side of the mobile device* on which actions are performed. Three main surfaces used to interact with a mobile device are identified: front, back, and lateral side.

The design space is elaborated from well-established design characteristics from the existing literature for eyes-free and one-handed interaction with mobile devices. The key contribution of this design space lies in its power to guide the design of eyes-free one-handed interaction techniques, as demonstrated in Chapter 5 and 6. We expect that our design space serves as a first step for researchers to explore new techniques for eyes-free one-handed interaction on mobile devices.

7.1.2 Mobile Eyes-free One-handed Interaction Techniques

From the existing literature, we noticed that one-handed techniques rely on graphical user interfaces. Such solutions miss the benefits of tangible user interfaces. Inspired by the *emergeables* concept [136] of tangible controls emerging from the surfaces of a mobile device, we then designed three interaction techniques based on our design space. The techniques rely on shape-changing tangible sliders capable of changing different design properties (see Figure 7-3).

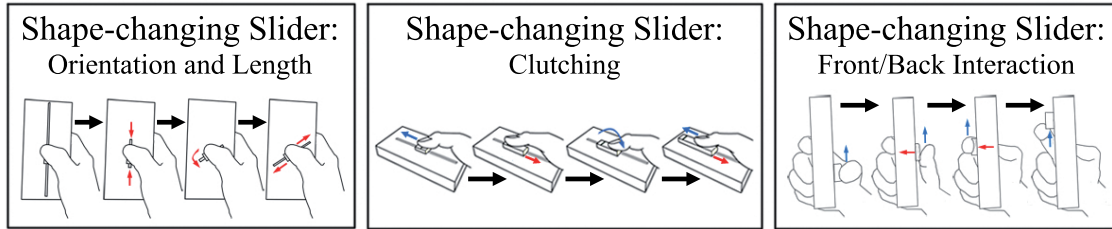


Figure 7-3: The three proposed techniques: Left) Changing the orientation and length of the tangible slider to fit within the thumb’s functional area; Middle) An extendable tangible slider that supports thumb-clutching movements to maintain operation within the thumb’s functional area; Right) A dual-side tangible slider that supports index finger operation on the back surface for reaching targets outside the thumb’s functional area.

Our first technique relies on changing the length and the orientation of a shape-changing tangible slider in order to facilitate one-handed interaction and support eyes-free interaction. In a controlled experiment, four different designed solutions of tangible sliders are evaluated: a large-vertical slider, a large-tilted slider, a small-vertical slider, and a small-tilted slider. Results show that: 1) small sliders perform slower than larger sliders due to their smaller motor scale, and 2) the orientation of the slider has no influence on performance.

Our second technique relies on clutching with the thumb on a shape-changing tangible slider in order to support eyes-free one-handed interaction. In a first experiment, a large tangible slider knob, that enables thumb-clutching, outperformed direct manipulation with a conventional (small) tangible slider knob. In a second experiment, we built and evaluated an actuated tangible prototype with a smaller knob that maintain the benefits of the large knob while improving portability. Results show that, when acquiring targets far from the thumb’s reach, thumb-clutching on an actuated prototype outperforms direct manipulation on a graphical conventional slider. However, the actuation motion disrupts interaction (i.e. participants stopped operating the slider while it is actuating). In a third experiment, we refined the actuated tangible prototype by reducing its thickness (-20mm). We then, studied the impact of actuation on eyes-free interaction. Results show that the actuated prototype performs

equally well in both blinded and non-blinded conditions and outperforms a graphical extendable slider.

Our third technique relies on Front- and Back-of-Device interaction with a shape-changing tangible slider in order to support eyes-free one-handed interaction. In a first experiment, we evaluated three different shape transitions in order to inform the best design to facilitate changing operation between front to back sides of a mobile device. Results show that “morphing-in” and “morphing-out” actuation motions of the slider’s knob do not disrupt interaction, and an instant shape transition was preferred over a gradual one. In a second experiment, we studied dual-side (front and back) interaction in comparison with thumb-clutching and direct manipulation for reaching targets far from the thumb’s reach. Results show that dual-side interaction outperforms the other conditions while providing a stable handgrip. In a third experiment, we evaluated the same conditions but for reaching targets close to the thumb’s reach. Results show that although a conventional tangible slider outperforms our dual-side approach, our solution supports a stable handgrip.

From the performed studies, we summarize the following:

- Using a long conventional tangible slider on the front side of the mobile device proved to be an efficient way to acquire targets over short distances (below 70mm approximately). However, operation beyond this threshold provokes hand movements (i.e. handgrip changes and hand relocations) that can be uncomfortable and unstable: a correlation between handgrip changes and the perception of security (i.e. risk of device being dropped) was experimentally observed for different body postures in [41]. Furthermore, mobile situations increase the hand oscillation [13], which could ultimately make the user drop the device if it is not being held properly.
- Enhancing the reachability of the thumb through clutching proved to be a promising way to acquire targets over long distances (200mm approximately). Thumb-clutching on extendable knobs located on the front side of the mobile device allows operation with long sliders and thus avoiding the scaling effect

present on small sliders. Furthermore, thumb-clutching movements also allow operation with a stable handgrip.

- Using dual-side interaction (for operation between the front and back side of a mobile device) with the thumb and the index finger proved to be a promising way to acquire targets over medium distances (100mm approximately). Dual-side interaction not only outperforms (-0.17s) direct manipulation supported by a conventional tangible slider but also allow operation with a stable handgrip.
- Shape transition is a key element when designing controls that automatically change shape while being manipulated. We observed that the actuation of the dual-side interaction technique had a lower impact on performance (-0.83s) than the actuation of the thumb-clutching technique. The two actuated solutions of chapter 5 and chapter 6 differ on the orientation of the shape transition. Participants claimed that the extension motion of the thumb-clutching technique was distracting since the slider knob actuated on the opposite direction of the thumb's movement. On the contrary, a "morphing-in/out" motion does not disrupt interaction on an actuated slider. We thus, suggest avoiding a shape transition opposite to the direction of the thumb's movement for tangible controls operated with the thumb.
- The tested shape-changing tangible approaches (an extendable tangible slider and a dual-side tangible slider) do not require the user's visual attention to be operated. This suggest that the motion of shape-changing tangible controls do not disrupt users from being eyes-free.

7.2 Limitations

From the performed studies, we consider that the implementation of the prototypes could be improved. For this, we consider three main limitations to be addressed: the actuation, the thickness and the friction of the prototypes.

7.2.1 Speed and Noise of the Actuation

The first limitation of our studies with actuated sliders was the speed of actuation. The used servomotors operated at 130 revolutions per minute at 6 volts. Such a speed could have not been optimum for the performed studies. For instance, we observed that the performance time of thumb-clutching movements was slower with actuated sliders in comparison with a large slider’s knob that simulated an already extended knob. We therefore consider important to identify the minimum speed of actuators that has no impact on interaction, particularly when interacting with shape-changing tangible sliders that support clutching (Section 5.6) and dual-side interaction (front and back) (Section 6.4).

In order to generalize the impact of the speed of actuation on performance, we consider important to evaluate other shape-changing tangible controls. For instance, a rotary dial that expands/shrinks according to the parameter that is being controlled.

We also consider that the noise of actuation could have an impact on the interaction. Although the actuators used for the prototypes in Chapter 4, 5 and 6 (pages 73, 81 and 131) were noisy, none of the participants made comments regarding the noise. However, we consider important to evaluate if the noise of the actuators could be used by users as feedforward to know the state of the actuation motion (e.g., when thumb-clutching with an actuated tangible slider, participants wait until the actuation noise finishes to land the thumb on the slider).

7.2.2 Thickness

The second limitation of our studies is related to the thickness of the tested prototypes. Existing studies have shown how the thickness of a mobile device could not only affect the user’s performance in a pointing task [97], but also affect the way users hold the device with only one hand [12]. The thickness of our prototypes ranged from 20mm (see Sections 5.2, 5.6 and Chapter 6) to 40mm (see Section 5.4 and 5.5). Although the current market of smartphones offers devices up to 14.8mm thick (e.g., Trekker-M1 [37]) most modern devices present a thickness of 7.7mm (e.g., iPhone X

[4]). We then consider that our bulky tangible prototypes could have force participants to adopt unfamiliar handgrips in comparison with commercial mobile devices. Current linear actuators and servomotors present dimensions that limit the design of thinner prototypes. Envisioning a future with miniaturized actuators, we consider important to re-evaluate our approaches with such a technology to ensure a handgrip closer to the ones used on modern mobile devices.

7.2.3 Friction

The third limitation related to our studies is the friction of the extendable tangible prototypes from Section 5.5 and 5.6. The experiments performed on those sections focused on study interaction far from the functional area of the thumb and thus, requiring sliders with a long travel length. However, commercial sliders only range from 15mm to 100mm. We then built two actuated tangible sliders with a 3D printer. The resulting surface of the printed sliders was not completely smooth. In order to improve the sliding of the knob, the surfaces were polished and lubrication was used. However, when compared to the graphical sliders displayed on the smooth surface of touchscreens, the difference was perceivable. Three participants from the experiments in Section 5.5 and 5.6 commented that the initial force required to start moving the tangible knob was bigger in comparison with the graphical knob. Despite of this, the visual attention required by the graphical slider had a bigger impact on interaction as the graphical slider performed worst when acquiring far targets. Nonetheless, we consider that the friction is a relevant parameter to take into consideration during the implementation of tangible sliders.

7.3 Perspectives

We have identified a number of directions in which the presented contributions could be further improved. We will present them in two categories: short-term and long-term perspectives.

7.3.1 Short-Term Perspectives

7.3.1.1 Exploring the Shape-changing Phase

We experimentally observed that the orientation of the motion of actuated sliders could impact the interaction (Section 5.1). A negative effect on performance was found from an actuated slider that simulates an extension motion in the opposite direction of the thumb’s movement (Section 5.3). On the contrary, no impact on performance was found with a perpendicular motion of an actuated slider in relation to the thumb’s movement (Chapter 6). This is a very important observation for the design of any system-controlled shape-changing user interface [134]. We then encourage the research community to further explore the impact that different shape-changing properties (e.g., orientation, form, volume, texture) of a tangible interface have on interaction during the actuation phase. For instance, evaluating the impact that the actuation of the volume (i.e. height, width and thickness) of the slider’s knob has on interaction during manipulation. This research avenue can be extended to study other shape-changing tangible controls like actuated rotary dials [160].

Because we studied shape-changing tangible controls that are manipulated by the users, the changing phase is crucial. This opens up an under-explored research avenue in the domain of shape-changing user interfaces [46, 59, 61, 65, 163, 139, 133, 185].

7.3.1.2 Exploring Multiple Shape-changing Controls

We also encourage the research community to study interaction with multiple shape-changing tangible sliders in the context of adjustment of different continuous parameters (e.g., controlling the RGB levels of a projector). Such a study would combine the advantages of tangible widgets on-demand as presented by the *Emergeables* concept [136] (see Section 4) with the benefits of shape-changing tangible controls for eyes-free one-handed interaction (see Sections 5 and 6). We particularly encourage the study of the challenges that could arise when operating multiple tangible controls in a one-handed manner. For instance, studying the shape transition when changing operation from one tangible control to another to avoid accidental operations on other

tangible controls.

7.3.1.3 Exploring the Lateral Side of the Mobile Device

As described in the design space, the lateral side of mobile devices has potential to serve as a complementary input (as done with the back side in the interaction technique from Chapter 6) to facilitate thumb interaction on the front side. In Section 3.2, we described existing works that make use of tangible interaction on the lateral side of the mobile device. However, such techniques were not designed to facilitate one-handed interaction. We encourage the research community to study how the lateral side could be further exploited for interaction with continuous controls. For instance, evaluating the performance of a slider on the lateral side of the mobile device that users could operate with the remaining fingers in order to reach targets outside the thumb's comfortable area. Furthermore, a study of the functional area of the fingers on the lateral side in order to inform the design of new interaction techniques would be beneficial for the community.

7.3.1.4 Ecological Validity

In order to extend the validity of our studies, we encourage the research community to further test our approaches with lead users [176] of sliders, such as audio engineers. Indeed, the work presented in this thesis was heavily inspired by the needs of such professionals in their work environment. Since audio engineers operate tangible sliders in different ways (e.g., using two fingers in a pinch-like gesture or using only one finger), we consider important to evaluate if the proposed interaction techniques (i.e. clutching and dual-side interaction) present a challenge for operation of the slider. We consider the validation, both qualitatively and quantitatively, of our approaches by such lead users as highly relevant and could lead to new techniques to facilitate interaction with sliders on mobile devices. However, during the development of this thesis, we did not have time to conduct experiments with audio engineers.

7.3.2 Long-Term Perspectives

7.3.2.1 Responsive Design for Shape-Changing Tangible User Interfaces

The *Emergeables* concept [136], presented in Chapter 4, relies on shape-changing mobile devices capable of “morphing-out” tangible controls out of their display surface in order to support eyes-free interaction. Such a concept raise the question of the design of such tangible user interfaces: are graphical user interfaces’ design guidelines sufficient for the design of tangible user interfaces’ layouts? We consider that this is highly improbable: graphical sliders on mobile devices with Android operating systems present a knob size of 12px (approximately 4mm) [53], whereas design guidelines for tangible slider knobs recommend a size of at least 10mm [93]. Hence, layouts for tangible user interfaces will probably present less elements on the interface in order to keep the interface operative.

Furthermore, in Chapter 5, we went a step further and envisioned tangible controls that do not only protrude out of the mobile device’s surface but can also shape-change in order to facilitate one-handed interaction. Such shape-changing tangible controls raise the issue of the layout of the interface when tangible controls change their shapes. For instance, a rotary dial that increases its diameter within an interface made of other elements like icons, text and buttons. Currently, responsive web design [111] is an approach that substitutes static layouts by flexible layouts that allow a relative placement of the interface’s elements according to the size of the device’s screen. In this way, website interfaces are able to adapt themselves to fit elements and facilitate navigation on different sizes of screen. We consider such an approach as a possible solution to tackle the problem of interfaces that include shape-changing tangible controls. Future work under such an approach could lead to design guidelines for responsive design on shape-changing tangible user interfaces, and probably, narrow the gap between designing for graphical and tangible user interfaces.

7.3.2.2 From Graphical to Tangible and Back

The *Emergeables* concept [136] presented in Chapter 4 envisions shape-changing mobile devices in which the graphical controls displayed on their screen surface can “morph-out” and present a tangible version. Such shape-changing mobile devices will display graphical controls (e.g., buttons, sliders and rotary dials) when the user is looking at the screen. When the user changes her/his visual attention away from the device, then the graphical controls transition into tangible ones. However, it is not clear how the transition from graphical to tangible should be started in order to avoid disrupting the interaction.

Existing studies from the literature (e.g., [88, 91, 185]) and the work presented in Chapter 5 and 6 rely on the user to start the shape-changing transition, namely, *directly controlled shape change* [135]. However, such an approach can disrupt the interaction [88, 91]. Thus, it is necessary to explore other approaches to avoid disrupting the interaction. In addition to *directly controlled shape change*, Rasmussen *et al.* [135] propose three other approaches: *indirectly controlled shape change*, *system controlled shape change* and *negotiated shape change*. Considering these approaches, the question is: which transition approach minimizes the disruption on the interaction?

Furthermore, we envision that these tangible controls could also change their size (e.g., height and width), and thus, the interface layout should adapt to fit the re-sized control. This could lead to the removal of other elements from the interface to allow the space required by the re-sized tangible control.

In this context, when the user looks back at the mobile device’s screen, several solutions must be studied: should the tangible control go back to a graphical version? and if so, should the mobile device keep the new interface’s layout or revert back to the previous one?

7.4 Vision of the Future

Tangible sliders could be beneficial for one-handed interaction on current mobile applications that make use of sliders to control continuous parameters. For instance, when adjusting the screen brightness, the user's thumb could easily drift away from the knob since the thumb's movement follows a parabolic trajectory [13]. Envisioning a shape-changing mobile device capable of rendering a tangible slider knob, the user could then feel if her/his thumb drifting away from the knob. The user could then re-adjust her/his handgrip to avoid stopping the operation of the tangible slider. Such a solution could be highly beneficial for situations in which the user is controlling a distant appliance with a mobile device. For instance, with a shape-changing mobile device capable of rendering tangible sliders for the Philips Hue application [130], users could change different color parameters of a lamp in a room. Moreover, such an action could be performed without looking at the device to change operation from one slider to the other due to the tangible aspect of the sliders.

Another common example of sliders on mobile devices is as scroll bars for fast exploration of a document or website. These sliders are usually located on the right border of the screen. Since handgrips on mobile devices usually enable a comfortable operation of the thumb near the center of the screen [85], interaction with scroll bars can be uncomfortable. For such situations, we envision that our dual-side tangible slider could facilitate one-handed interaction. Users can trigger the front tangible knob anywhere on the display through a gesture, for instance, making pressure on the screen. The gesture would start the rendering of a tangible slider knob underneath the user's thumb position. In this way, the user could invoke the tangible slider in the most comfortable location for her/his thumb and index finger. Although finger occlusion could be present on the front side, we speculate that the large screens of modern mobile devices would provide enough display to users when searching for elements when user the slider as a scroll bar.

Regarding a dual-side tangible slider, such an interaction technique would not be available if the mobile device is covered with a protective case. Since we envision

a shape-changing mobile device which back side is fully interactive and deformable, we expect that covers would be hollow on the back in order to enable back-of-device interaction.

Synthèse en Français

Avant-propos

Ce chapitre fournit une traduction de l'introduction et de la conclusion ainsi qu'un résumé de chaque chapitre en français.

Introduction

Les dispositifs mobiles sont devenus essentiels pour nos activités quotidiennes. Les smartphones et tablettes permettent aux utilisateurs d'effectuer des tâches qui n'étaient auparavant possibles que sur des ordinateurs de bureau. Par exemple, les utilisateurs de smartphones peuvent consulter leurs e-mails, se localiser eux-mêmes en temps réel sur une carte, jouer à des jeux vidéo et créer des documents avec un logiciel de traitement de texte. De plus, l'aspect portable de tels dispositifs permet aux utilisateurs de l'emporter avec eux n'importe où. Cela a eu un impact sur la préférence des utilisateurs pour les dispositifs mobiles, ce qui se reflète dans la tendance actuelle de consommation : une étude de marché [74] a révélé que le marché des ordinateurs personnels avait diminué de 5,7% entre 2015 et 2016, avec une livraison totale de 260 millions d'unités. Au contraire, une autre étude de marché [75] a annoncé une croissance de 2,5% du marché des smartphones, avec une livraison totale de 1.451 millions d'unités. La pertinence des dispositifs mobiles se reflète également dans le nombre d'utilisateurs. Android à lui seul détient un marché de 2 milliards d'utilisateurs [51] (en considérant les tablettes et les smartphones). Par conséquent, les problèmes d'utilisabilité de ces dispositifs sont très importants à résoudre.

Dans le domaine de l'interaction homme-machine (IHM), cette étude doctorale est dédiée à l'interaction avec de tels dispositifs mobiles. En particulier, nous nous concentrons sur deux problèmes majeurs :

- **L'attention visuelle requise pour utiliser des dispositifs mobiles :** Depuis l'introduction des écrans tactiles, l'interaction mobile repose principalement sur une manipulation directe avec les doigts sur une surface tactile plane pour manipuler les éléments d'une interface graphique. L'absence de retour haptique des écrans tactiles oblige les utilisateurs à regarder leur dispositif afin d'interagir avec les éléments affichés à l'écran. Une telle dépendance visuelle devient problématique dans des situations où l'utilisateur doit concentrer son attention visuelle ailleurs, par exemple, lorsqu'il parle à une personne ou traverse une rue. Ce problème est étudié dans le domaine de l'IHM et les chercheurs utilisent le terme *interaction sans regarder* pour désigner le fonctionnement du dispositif mobile sans le regarder.
- **L'utilisation du dispositif mobile avec une seule main :** il existe des situations dans lesquelles l'utilisation avec une seule main est requise, par exemple, écrire sur du papier des informations obtenues sur le dispositif mobile ou porter un sac de courses tout en vérifiant l'horaire du bus. Malgré cela, les dispositifs mobiles sont difficiles à utiliser à une seule main en raison de leur taille. En conséquence, les utilisateurs ne peuvent pas atteindre toute la zone de l'écran tactile avec leur pouce. L'interaction à deux mains avec le dispositif mobile résoudrait ce problème. Toutefois, des études ont montré que les utilisateurs préfèrent utiliser les dispositifs mobiles avec une seule main [71, 85]. Les chercheurs utilisent le terme *interaction à une main* pour désigner l'utilisation du dispositif mobile avec une seule main.

Cette recherche doctorale porte sur ces deux problèmes, à savoir *interaction sans regarder l'écran et à une main*. Il s'agit d'un vaste sujet de recherche et nous nous concentrons sur le cas des contrôles de paramètres continus, et en particulier de l'interaction avec les curseurs sur les dispositifs mobiles. Le réglage de paramètres continus

avec des curseurs sur les dispositifs mobiles est une tâche courante dans un environnement professionnel. Par exemple, les ingénieurs du son fixent le volume sonore d'un lieu avant un concert [88], et les scientifiques filtrent les données affichées sur un écran de la taille d'un mur [80]. Ce type de tâche est également présent dans un environnement domestique, par exemple, une personne à la maison réglant le volume du son des haut-parleurs [18] ou la couleur de la lumière [130]. Bien que d'autres solutions permettent aux utilisateurs de sélectionner une valeur parmi une plage continue de valeurs (par exemple, par l'orientation du doigt [114] ou la pression sur l'écran [152], ou en utilisant d'autres widgets tels que les boutons rotatifs et les molettes), ce travail de doctorat est axé sur les curseurs pour des raisons de rétro-compatibilité. Une étude récente [88] montre que les principaux utilisateurs (voir [176]) de curseurs, tels que les ingénieurs du son et les graphistes, préfèrent exploiter leur expertise avec des interfaces familières même si d'autres solutions pourraient leur permettre un gain de performance.

Le scénario suivant (traité plus en détail au chapitre 2) illustre la nécessité de certains utilisateurs de curseurs d'utiliser les curseurs sur un dispositif mobile à une main et sans regarder l'écran : *Bob est l'ingénieur du son d'un groupe qui se produira en direct à l'extérieur. Bob est en charge du réglage du niveau de volume des instruments provenant des différents haut-parleurs autour du lieu. Pour cela, Bob utilise une console de mixage statique présentant de nombreux grands curseurs physiques positionnés verticalement. Cependant, l'emplacement de la console de mixage ne permet pas à Bob de se déplacer autour du lieu pour chercher des points sonores problématiques et ajuster le volume des instruments. Pour résoudre ce problème, Bob utilise une application sur son téléphone portable qui affiche une interface graphique imitant l'aspect physique de sa console de mixage. Cela permet à Bob de contrôler les curseurs de la console de mixage à distance. En plus, Bob doit communiquer avec les musiciens à distance. Bob communique avec les musiciens par signes (gestuels). Bob utilise une main pour interagir avec son téléphone portable et l'autre pour communiquer. Enfin, Bob doit garder son attention visuelle sur la scène afin d'obtenir le retour des musiciens.*

Puisque les curseurs graphiques sur les dispositifs mobiles peuvent être longs et positionnés verticalement ou horizontalement, atteindre tous les secteurs du curseur peut être problématique lors de l'utilisation d'un smartphone avec une seule main. De plus, leur nature graphique nécessite l'attention visuelle des utilisateurs. Cette recherche doctorale traite ces deux problèmes avec les curseurs graphiques grâce à la conception de techniques d'interaction mobiles sans regarder l'écran et à une main basées sur des curseurs.

Objectifs et Méthodes

L'objectif de la recherche menée est d'améliorer l'interaction avec des curseurs sur les dispositifs mobiles. Comme indiqué ci-dessus, l'interaction à une seule main et l'attention visuelle requise par les interfaces graphiques sont des problèmes majeurs qui affectent l'interaction avec les dispositifs mobiles. Dans ce contexte, la question de recherche que nous abordons est la suivante : comment améliorer l'interaction sans regarder l'écran et à une main avec un curseur sur un dispositif mobile ? Pour répondre à la question, nous avons adopté une approche en deux étapes (voir Figure 1).

Tout d'abord, nous établissons les bases de la conception de nouvelles techniques d'interaction pour une interaction sans regarder l'écran et à une main sur des dispositifs mobiles. Pour cela :

1. Nous établissons un espace de conception à partir de notre analyse des techniques existantes en matière d'interaction sans regarder l'écran et à une main. L'espace de conception est organisé en fonction de l'ensemble des caractéristiques identifiées pour une interaction sans regarder l'écran et à une main sur des dispositifs mobiles ;
2. Nous décrivons un concept d'interaction sans regarder l'écran sur dispositifs mobiles appelé *Emergeables*² [136] afin d'illustrer le dispositif mobile du futur qui

²Nous souhaitons préciser que l'auteur de cette thèse n'est pas l'auteur principal du concept *Emergeables* [136]. Cependant, il faisait partie de l'équipe de recherche au sein de laquelle il a été

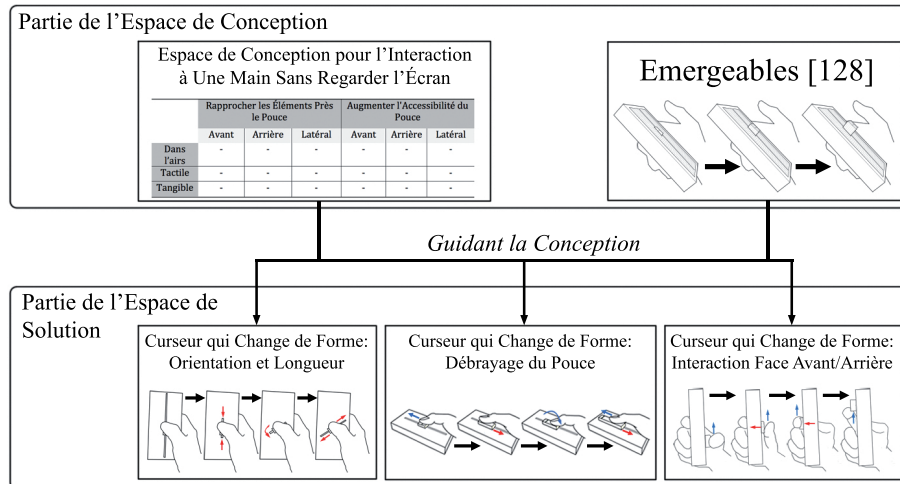


FIGURE 1 : La démarche de recherche suivie : un espace de conception sur l'interaction sans regarder l'écran et à une main, et le concept d'*Emergeables* [136] ont été utilisés pour orienter la conception de nouvelles solutions d'interaction sans regarder l'écran et à une main. Les techniques changent différents aspects du curseur, par exemple l'emplacement ou la taille du bouton, ou l'orientation ou la longueur du curseur (direction des flèches rouges) afin de faciliter les opérations et/ou la saisie (direction de la flèche bleue) avec le pouce ou l'index.

pourrait prendre en charge des nouvelles techniques d'interaction sans regarder l'écran et à une main.

Ensuite, nous validons la capacité de l'espace de conception à guider la conception de nouvelles techniques d'interaction. Trois nouvelles techniques d'interaction pour une interaction sans regarder l'écran et à une main ont été conçues sur la base de l'espace de conception et du concept d'*Emergeables* [136]. *Emergeables* envisage des dispositifs mobiles qui changent de forme et sont capables de faire apparaître des contrôles tangibles hors de la surface d'affichage. Les techniques conçues reposent sur des curseurs tangibles qui changent de forme et sont capables de modifier différentes propriétés de conception (par exemple, l'orientation, la longueur et le côté du dispositif mobile où les curseurs sont présentés). Pour chaque technique conçue, nous avons effectué des évaluations expérimentales.

conçu et développé. L'auteur de cette thèse a réalisé le prototype haute résolution et a également participé à l'analyse des données recueillies lors de l'expérience.

Contributions

Dans le domaine d'IHM, cette thèse contribue aux domaines de l'interaction mobile et de l'interaction tangible. Les principales contributions sont :

1. Un espace de conception pour une interaction sans regarder l'écran et à une main sur les dispositifs mobiles.
2. La conception et l'évaluation de trois techniques d'interaction pour une interaction sans regarder l'écran et à une main avec des curseurs sur les dispositifs mobiles.

Notre première contribution est un espace de conception pour une interaction sans regarder l'écran et à une main avec les dispositifs mobiles. L'espace de conception est structuré autour de trois propriétés dérivées des travaux existants dans la littérature :

1. la stratégie utilisée pour faciliter l'interaction à une main ;
2. l'approche utilisée pour rendre possible l'interaction sans regarder l'écran ;
3. le côté de le dispositif mobile où l'interaction a lieu.

Cet espace de conception sert à guider la conception de techniques d'interaction sans regarder l'écran et à une main. Nous avons utilisé cet espace pour la conception des techniques que nous présenterons aux chapitres 5 et 6.

Notre deuxième contribution comprend trois nouvelles techniques basées sur le concept d'*Emergeables* [136]. Elles ont été conçues en fonction de l'espace de conception présenté précédemment (voir Figure 1-1). Les techniques reposent sur des curseurs tangibles qui changent de forme et qui sont capables de modifier différentes propriétés de conception afin de faciliter l'interaction à une main.

La première technique vise à faciliter l'interaction à une seule main en modifiant l'orientation et la longueur des curseurs. Dans une expérience contrôlée, quatre conceptions différentes de curseurs tangibles sont testées pour une tâche de pointage à distance : un grand curseur vertical, un grand curseur incliné, un petit curseur

vertical et un petit curseur incliné. Les résultats montrent que : 1) l'orientation du curseur n'a aucune influence sur les performances, et 2) les petits curseurs ont des performances plus faibles par rapport aux curseurs plus grands en raison de l'espace moteur plus réduit.

La seconde technique repose sur le débrayage du pouce sur un curseur tangible extensible pour faciliter l'interaction à une main tout en soutenant l'interaction sans regarder l'écran. Dans une première expérience, un gros bouton de curseur tangible, qui permet le débrayage du pouce, est plus performant que la manipulation directe avec un petit bouton de curseur tangible classique. Dans une seconde expérience, nous construisons et évaluons un prototype tangible actionné qui prend en charge les avantages du gros bouton tout en améliorant la portabilité. Les résultats montrent que le débrayage du pouce sur un prototype actionné surpasse le curseur graphique classique pour les cibles éloignées de la portée du pouce. Cependant, le mouvement d'actionnement perturbe l'interaction. Dans une troisième expérience, nous testons une nouvelle version du prototype tangible actionné (avec une épaisseur réduite) pour étudier l'impact du mouvement d'actionnement sur l'interaction sans regarder l'écran. Les résultats montrent que le prototype actionné fonctionne aussi bien en conditions aveugles que non aveugles et surpasse les performances d'un curseur extensible graphique.

La troisième technique implique une interaction face avant et arrière de le dispositif avec un curseur tangible qui change de forme. Dans une première expérience, nous évaluons différentes transitions de forme entre les faces avant et arrière. L'objectif est d'informer de la meilleure conception possible pour faciliter le changement d'opération entre les faces avant et arrière. Les résultats montrent que les mouvements d'actionnement perpendiculaires au mouvement du pouce ne perturbent pas l'interaction et qu'une transition de forme instantanée était préférable à une transition progressive. Dans une deuxième expérience, nous comparons l'interaction sur les deux faces (avant et arrière) avec le débrayage du pouce et une manipulation directe pour atteindre des cibles éloignées de la portée du pouce. Les résultats montrent que l'interaction sur les deux faces surpasse les autres conditions tout en fournissant une

prise en main stable. Dans une troisième expérience, nous évaluons les mêmes conditions mais pour atteindre des cibles proches de la portée du pouce. Les résultats montrent que, même si un curseur tangible conventionnel surpasse notre approche face avant/arrière, notre solution permet une prise en main stable.

Structure du Document

Le document est structuré comme suit (voir Figure 2) :

- Dans le chapitre 2, nous présentons notre sujet de recherche : l'interaction sans regarder l'écran et à une main avec des dispositifs mobiles.

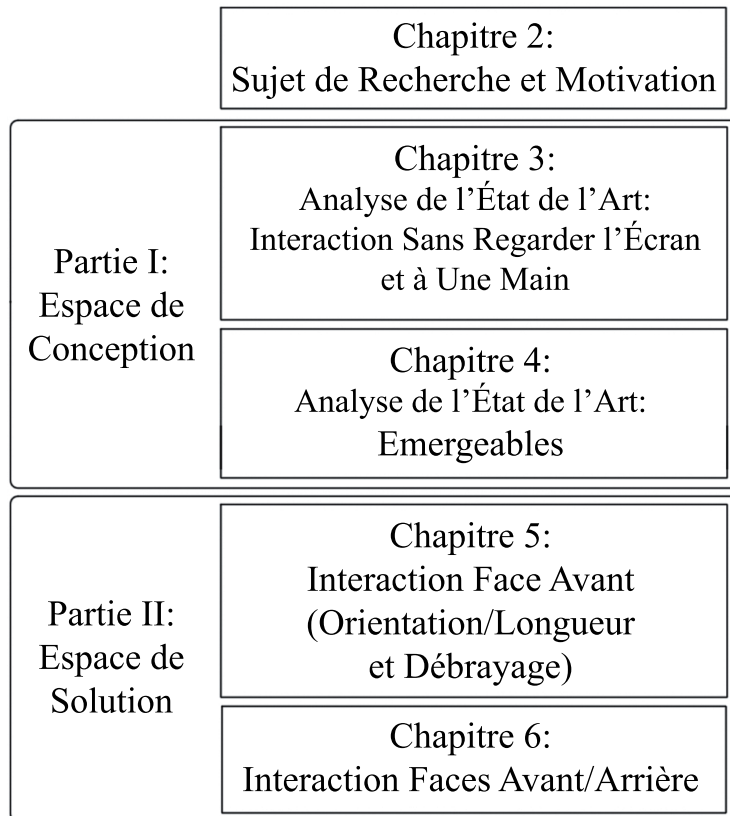


FIGURE 2 : Structure de la thèse.

La Partie I Espace de Conception est composée de deux chapitres dans lesquels nous établissons des caractéristiques clés pour la conception de nouvelles techniques

d'interaction sans regarder l'écran et à une main.

- Dans le chapitre 3, nous présentons une revue des techniques existantes d'interaction sans regarder l'écran et à une main. Nous présentons ensuite notre espace de conception, qui se concentre sur l'interaction sans regarder l'écran et à une main.
- Dans le chapitre 4, nous présentons un concept (introduit pour la première fois dans [136]³) pour une interaction sans regarder l'écran avec des contrôles tangibles qui changent de forme dynamiquement sur des dispositifs mobiles. Nous avons ajouté en Annexe une expérience que nous avons réalisée pour valider le concept avec les curseurs linéaires et rotatifs.

La Partie II Espace de Solution est composée de deux chapitres décrivant les techniques d'interaction que nous proposons pour une interaction sans regarder l'écran et à une main avec des curseurs.

- Dans le chapitre 5, nous présentons quatre expériences que nous avons effectuées afin d'évaluer les performances de deux de nos techniques : 1) le changement de l'orientation et de la longueur des curseurs, et 2) l'opération des curseurs par embrayage. Les techniques sont conçues pour une interaction face avant du dispositif mobile.
- Dans le chapitre 6, nous présentons trois expériences que nous avons effectuées afin d'évaluer les performances de notre dernière technique, à savoir l'interaction faces avant et arrière du dispositif avec des curseurs.

Description des Chapitres

Chapitre 2 : Sujet de Recherche et Motivation

Dans ce chapitre, nous présentons les trois thèmes clés de nos travaux de recherche liés à l'interaction avec des dispositifs mobiles : l'interaction sans regarder l'écran,

³l'auteur de cette thèse faisait partie de l'équipe de recherche

l'interaction à une main et les curseurs.

L'interaction sans regarder l'écran vise à minimiser l'attention visuelle requise par les interfaces graphiques sur les dispositifs mobiles. Plusieurs situations obligent les utilisateurs à utiliser leurs dispositifs mobiles sans regarder l'écran. Par exemple, contrôler le volume sonore des haut-parleurs à la maison tout en descendant les escaliers pour ouvrir la porte d'entrée ou en traversant une rue. De plus, dans le cas d'une tâche requérant l'attention visuelle, obliger l'utilisateur à regarder l'écran du dispositif mobile pour interagir peut avoir un impact négatif sur les performances de réalisation de la tâche.

L'interaction à une main fait référence à l'utilisation d'une seule main pour interagir avec des dispositifs mobiles. L'interaction à une main, la plus répandue, repose sur l'interaction tactile du pouce sur l'écran, car il s'agit du seul doigt disponible pour interagir avec l'écran du dispositif mobile. Cependant, en raison de l'anatomie de la main, l'amplitude de mouvement du pouce est limitée. Une telle restriction de mouvement est un problème pour une interaction à une main lors de la manipulation des dispositifs mobiles les plus modernes : les utilisateurs ne peuvent pas atteindre toutes les zones de l'écran du dispositif avec le pouce. Les mouvements de la main (les changements des prises en main et les déplacements du dispositif dans la main) nécessaires pour atteindre toutes les zones de l'écran sont inconfortables et peuvent provoquer la chute du dispositif.

Les curseurs constituent la classe de widgets la plus utilisée pour le réglage de paramètres continus sur les dispositifs mobiles. Ils sont largement utilisés pour contrôler :

1. les paramètres d'un dispositif mobile comme le volume sonore, la luminosité de l'écran ;
2. et les paramètres d'appareils distants connectés, comme la couleur de la lumière d'une lampe et le volume sonore d'une enceinte.

Cependant, l'utilisation de curseurs sur dispositifs mobiles soulèvent des problèmes d'utilisabilité. D'une part, les curseurs horizontaux de faible longueur offrent une faible précision en raison de la petite échelle de l'espace moteur (action de l'utilisateur).

D'autre part, les curseurs verticaux de grande longueur définissent des zones inaccessibles en raison des limitations de l'amplitude limitée des mouvements du pouce.

Après avoir introduit les trois thèmes de nos travaux de recherche, nous les avons ensuite illustrés ces trois thèmes clés de notre recherche en présentant un scénario de cas réels suivi de deux scénarios de cas futurs illustrant des exemples pratiques d'interaction sans regarder l'écran et à une main avec un curseur sur un dispositif mobile. Dans les trois scénarios présentés, les utilisateurs doivent tenir un dispositif mobile pour interagir avec un dispositif distant. Les utilisateurs doivent concentrer leur attention visuelle sur le point d'intérêt de la tâche qui est distinct et distant de l'écran du dispositif mobile. Ces scénarios motivent nos questions de recherche.

Parte I Espace de Conception, Chapitre 3 : Analyse de l'État de l'Art : Interaction Sans Regarder l'Écran et à Une Main

Dans ce chapitre, nous présentons les techniques existantes pour *l'interaction sans regarder l'écran* et pour *l'interaction à une main* avec des dispositifs mobiles. Nos travaux étant dédiés à l'interaction avec des curseurs, notre état de l'art inclut que les techniques de pointage et suivi. En effet il s'agit des deux types de tâche les plus courantes avec des curseurs pour la sélection d'une valeur dans une plage de valeurs (par exemple, la modification du niveau de luminosité de l'écran d'un dispositif mobile).

Nous structurons notre analyse des techniques existantes comme suit :

- D'abord, nous présentons les techniques existantes qui permettent *l'interaction sans regarder l'écran* des dispositifs mobiles. Nous structurons la présentation de ces techniques selon : 1) si les techniques impliquent de toucher le dispositif ou non (technique sans contact avec le dispositif), et 2) l'approche utilisée pour permettre une interaction sans regarder l'écran, par exemple une interaction sur-le-corps ou une interaction tangible.
- Ensuite, nous présentons les études existantes sur les techniques facilitant *l'interaction à une main* sur les dispositifs mobiles. Pour structurer la présentation

de ces techniques, nous les classons en fonction de la *stratégie utilisée pour faciliter l'interaction à une main* et de la *partie du dispositif mobile* sur laquelle l'interaction est effectuée.

Nous synthétisons enfin notre analyse des techniques existantes en présentant un espace de conception. L'espace de conception est organisé en fonction de l'ensemble des caractéristiques identifiées pour une interaction sans regarder l'écran et à une main. Cet espace de conception permet d'explorer de nouvelles techniques *d'interaction sans regarder l'écran et à une main* avec des dispositifs mobiles.

Parte I Espace de Conception, Chapitre 4 : Analyse de l'État de l'Art : Emergeables, Contrôles Dynamiques Tangibles sur des Dispositifs Mobiles qui Changent de Formes

Dans ce chapitre, nous présentons *Emergeables* – une démonstration de la manière dont des contrôles tangibles pourraient être créés de manière dynamique sur des dispositifs mobiles qui changent de forme. Le concept (introduit pour la première fois dans [136]) envisage un dispositif mobile dans lequel tout widget de contrôle peut apparaître sur sa surface (voir Figure 4-1) – offrant la souplesse d'une interface graphique, ainsi que les avantages d'une interface tangible. Afin de démontrer et de tester le potentiel d'*Emergeables*, deux prototypes ont été construits : 1) un prototype haute résolution, où les contrôles apparaissent sur la surface dans un ensemble de positions fixes ; et 2) un prototype basse avec un écran composé d'un ensemble de tiges qui peuvent monter ou descendre (rétractables) pour créer un contrôle manipulable par l'utilisateur. Cette solution basse résolution de la part la taille des tiges offre néanmoins une flexibilité de positionnement que le prototype haute résolution ne permet pas. A partir d'une expérience contrôlée (voir Annexe C, page 215), les résultats obtenus montrent le potentiel et les avantages du prototype haute résolution sur des contrôles tangibles émergentes en termes de précision, d'attention visuelle et de préférence de l'utilisateur.

L'aspect fondamental d'*Emergeables* [136] pour notre travail nous motive à présenter

le concept dans la Partie I Espace de Conception. De plus, *Emergeables* définit un concept qui, combiné à notre espace de conception du chapitre précédent (page 68), est à la base de nos contributions présentées dans la Partie II Espace de Solution (page 80). En effet, *Emergeables* autorise des interactions sans regarder l'écran grâce à l'interaction tangible (voir la section 3.1.3) et nous permet d'appliquer les approches pour l'interaction à une main actuellement dédiées aux interfaces graphiques (voir la section 3.2).

Parte II Espace de Solution, Chapitre 5 : Interaction Face Avant

La tendance actuelle des écrans tactiles a transformé la face avant des dispositifs mobiles en surface d'entrée principale. Quand une seule main est utilisée pour opérer des dispositifs mobiles, le pouce est le doigt le plus souvent utilisé pour interagir avec la face avant du dispositif. Cependant, le pouce a une amplitude de mouvement limitée en raison de contraintes anatomiques (voir la section 2.2.2.2, page 21) qui empêchent les utilisateurs d'atteindre toute la surface d'entrée du dispositif mobile.

Dans ce chapitre, nous explorons deux techniques d'interaction sans regarder l'écran et à une main lors de l'utilisation de curseurs sur des dispositifs mobiles. Les techniques sont basées sur le concept [136] (page 73). De plus, les techniques ont été conçues en fonction des caractéristiques de conception présentées dans l'espace de conception de la section 3.3 (page 68). Nous nous appuyons sur des widgets tangibles qui changent de forme pour permettre une interaction sans regarder l'écran et faciliter leur manipulation avec une seule main. Dans ce contexte, deux approches, décrites dans la section 3.3, sont possibles : rapprocher les éléments près du pouce ou augmenter l'accessibilité du pouce.

Notre première technique vise à rapprocher les éléments près de la zone fonctionnelle confortable du pouce. Nous étudions un curseur tangible dont l'orientation et la longueur varient afin d'être manipulé par le pouce dans sa zone fonctionnelle. Le curseur tangible peut s'agrandir/se contracter pour s'adapter à la zone confortable

du pouce (voir Figure 3, A-B) et changer son orientation de la verticale à la position inclinée (voir Figure 3, C-D) pour faciliter le mouvement du pouce [85]. De plus, l'aspect tangible du curseur permet un fonctionnement sans regarder le dispositif.

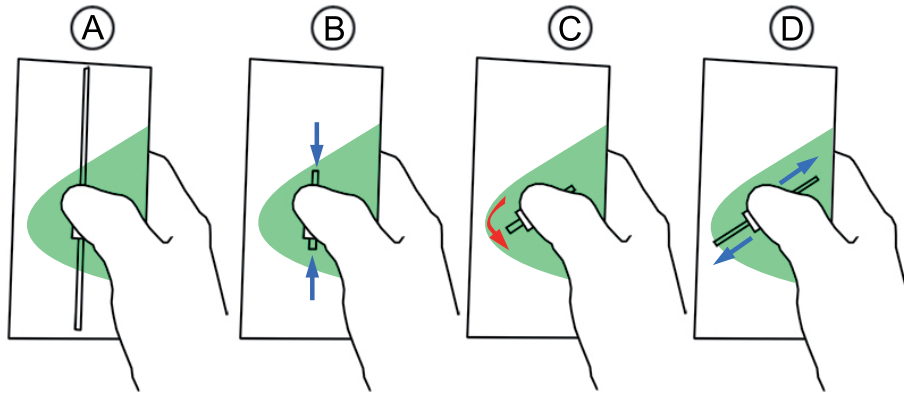


FIGURE 3 : (A) Un curseur tangible qui change de forme. (B) Le curseur peut se contracter/s'étendre (flèches bleues) pour s'adapter à la zone confortable du pouce (zone verte) lorsqu'il est utilisé d'une seule main. (C) Le curseur peut également changer d'orientation (flèche rouge) afin de faciliter les mouvements du pouce. (D) Le curseur incliné s'étend dans la zone confortable du pouce pour offrir une échelle plus grande dans l'espace moteur.

D'après l'expérience que nous avons menée, nous avons conclu que réduire la longueur du curseur afin de l'adapter à la zone fonctionnelle du pouce n'était pas une solution viable en raison de l'effet de mise à l'échelle de l'espace moteur. Au contraire, la modification de l'orientation des curseurs longs n'a aucune influence sur les performances. Néanmoins des travaux ont montré que les mouvements de flexion/extension (effectués sur les curseurs verticaux) sont plus faciles à réaliser que les mouvements d'adduction/abduction (réalisés avec les curseurs inclinés) [85].

Nous avons donc décidé d'explorer la seconde approche qui consiste à augmenter l'accessibilité du pouce.

Notre deuxième technique utilise des mouvements de débrayage du pouce sur un curseur tangible extensible pour atteindre les cibles situées en dehors de la zone fonctionnelle du pouce tout en évitant les changements de prise en main (voir Figure 4). Le bouton du curseur augmente sa longueur afin de permettre des mouvements de

débrayage du pouce. Lorsque le bouton est déplacé vers le haut, il est actionné vers le bas tout en maintenant le repère du curseur à la bonne position (voir Figure 4, A-B et C-D), et inversement. Afin de tester notre solution, nous avons d’abord construit un prototype basse fidélité d’un curseur tangible extensible, composé d’un très long bouton tangible. Ce prototype basse fidélité nous a permis de comparer les performances des mouvements de débrayage du pouce avec ceux de manipulation directe de curseurs tangibles conventionnels. Nous avons ensuite construit deux prototypes actionnés correspondant à des prototypes de plus haute fidélité d’un curseur tangible extensible.

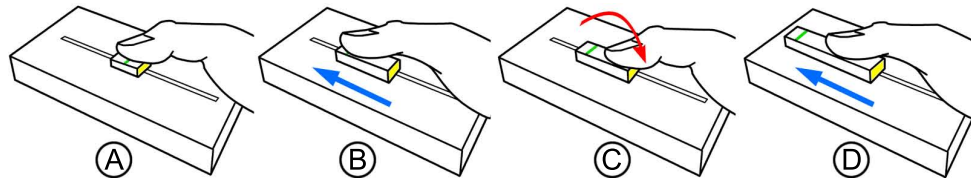


FIGURE 4 : Débrayage avec un curseur tangible extensible : (A), l'utilisateur place son pouce sur le bouton du curseur et (B) commence à pousser vers le haut (direction de la flèche bleue). (C) Lorsque cette action n'est plus confortable, l'utilisateur peut continuer à ajuster le paramètre contrôlé (comme indiqué sur la ligne de repère verte) en effectuant une action de débrayage, en tirant le pouce vers le bas jusqu'à la position de départ confortable. (D) Cela est possible car le bouton du curseur s'étend (côté jaune) dans le sens opposé.

D'après les expériences que nous avons menées, la solution tangible extensible facilite l'interaction à une seule main. Les mouvements de débrayage du pouce sont effectués à l'intérieur de la zone fonctionnelle du pouce, empêchant ainsi les changements de prise en main et les déplacements de main. De plus, son aspect tangible favorise une interaction sans regarder l'écran. Néanmoins, le mouvement d'extension du curseur perturbe l'interaction : l'utilisateur s'arrête de manipuler le curseur lors de sa déformation.

Parte II Espace de Solution, Chapitre 6 : Interaction Face Avant/Arrière

Dans ce chapitre, nous explorons une autre solution au problème de l'interaction sans regarder l'écran et à une main lors de l'utilisation de curseurs sur des dispositifs mobiles. La solution adopte une approche utilisée en interaction graphique (voir la section 3.2.2, page 65) : l'index (situé sur la face arrière du dispositif) sert d'entrée auxiliaire pour améliorer l'accessibilité du pouce sur la face avant.

Nous présentons un curseur tangible qui change de forme et capable de se métamorphoser sur les faces avant et arrière du dispositif mobile. Le bouton tangible du curseur apparaît sur la face avant pour permettre une utilisation avec le pouce. Quand le pouce atteint les limites de sa zone fonctionnelle, le bouton du curseur commence à se transformer de la face avant vers la face arrière du dispositif (voir Figure 5). Cela permet à l'utilisateur de continuer à manipuler le bouton avec l'index sur la face arrière du dispositif au-delà de la zone fonctionnelle du pouce, sans qu'il soit nécessaire de changer la prise en main. De plus, l'aspect tangible du curseur permet un fonctionnement sans regarder le dispositif.

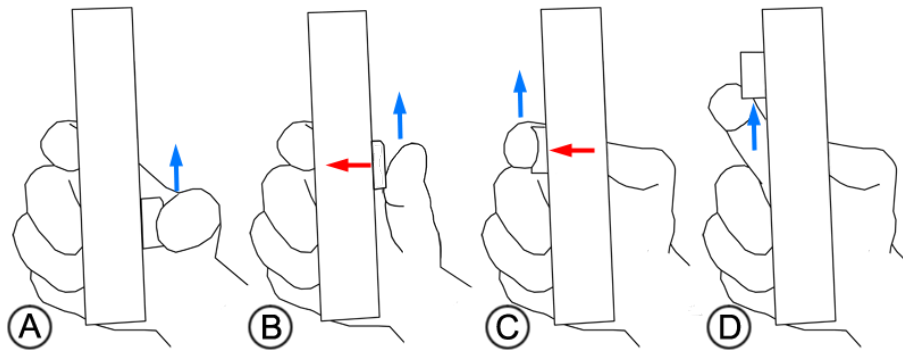


FIGURE 5 : Curseur tangible sur les deux faces (avant et arrière) : actionnement du bouton d'un curseur tangible de l'avant vers l'arrière. (A) l'utilisateur commence à faire glisser le bouton (direction de la flèche bleue); (B) lorsque l'élongation maximale du pouce est atteinte, le bouton commence automatiquement à se transformer (direction de la flèche rouge); (C) le bouton apparaît sur la face arrière du dispositif pour permettre à l'utilisateur (D) de continuer à contrôler le bouton avec l'index.

Notre solution présente des avantages pour différentes situations. D'une part, pour

les cibles éloignées de la zone fonctionnelle du pouce, notre solution surpasse la manipulation directe avec un curseur tangible conventionnel. D'autre part, pour les cibles proches de la zone fonctionnelle du pouce, bien que le curseur tangible conventionnel soit légèrement plus rapide, notre solution autorise une prise en main stable. Une telle fonctionnalité pourrait être souhaitée pour différents scénarios. Par exemple, les situations mobiles augmentent l'oscillation de la main, ce qui pourrait éventuellement provoquer la chute du dispositif de la main de l'utilisateur. (voir la section 2.2.2.3, page 25). De plus, il a également été démontré que les postures corporelles stationnaires (comme assis et couché) diminuaient la stabilité de la prise en main par rapport à une posture debout (voir la section 2.2.2.3). Enfin, une technique d'interaction sur les deux faces est perçue positivement en termes d'utilisabilité et de confort.


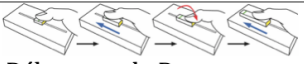
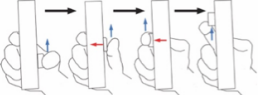
	Rapprocher les Éléments Près le Pouce			Augmenter l'Accessibilité du Pouce		
	Avant	Arrière	Côté	Avant	Arrière	Côté
Dans l'airs						
Tactile						
Tangible	 <p>Modification de l'Orientation et de la Longueur des Curseurs Tangibles</p>			 <p>Débrayage du Pouce sur un Curseur Tangible Extensible</p>		
				 <p> Curseur Tangible À Deux Face (Avant et Arrière)</p>		

TABLE 1 : Les curseurs tangibles qui changent de forme qui ont été présentés définissent de nouvelles techniques dans trois cellules inexplorées de l'espace de conception pour une interaction sans regarder l'écran et à une main avec des dispositifs mobiles : Rapprocher les éléments près du pouce et augmenter l'accessibilité du pouce (axe X); Interaction tangible (axe Y); Côtés avant et arrière (axe Z).

De plus, nos études ont également mis en lumière l'impact de la forme de la transition sur l'interaction. Ceci est un élément clé lors de la conception de contrôles qui changent automatiquement de forme lors de la manipulation. Nous avons observé que l'activation de la technique d'interaction sur les deux faces (avant et arrière) avait moins d'impact sur les performances que l'activation de la technique de débrayage du pouce du chapitre précédent. Les deux solutions déformables avec des actionneurs

du chapitre 5 et du chapitre 6 présentent deux paramètres différents en termes de la forme de la transition : l'orientation et l'amplitude du mouvement contrôlé par les actionneurs.

Enfin, avec notre technique d'interaction sur les deux faces et les deux techniques d'interaction présentées dans le chapitre 5, nous contribuons à l'espace de conception pour l'interaction avec des dispositifs mobiles d'une manière sans regarder l'écran et à une main (voir le Tableau 1).

Conclusion

Les dispositifs mobiles, comme les smartphones et les tablettes, sont, aujourd'hui, largement utilisés en raison de leurs multiples fonctionnalités qui nous aident dans nos activités quotidiennes. Dans le contexte de l'interaction mobile, les utilisateurs sont fréquemment confrontés à deux situations différentes : 1) utiliser les dispositifs mobiles tout en maintenant l'attention visuelle sur l'environnement, et 2) être capable de manipuler confortablement le dispositif mobile avec une seule main. La première situation fait référence à une interaction sans regarder l'écran, un besoin présent dans un large éventail de scénarios (par exemple, manipuler le dispositif mobile en traversant une rue, en descendant les escaliers ou en interagissant avec d'autres personnes). La seconde situation fait référence à l'interaction à une main, un besoin très fréquent lorsque l'autre main n'est pas disponible (par exemple, lorsqu'on porte un sac) ou pour des préférences de confort. Nous nous sommes concentrés sur ces deux problèmes, à savoir *l'interaction sans regarder l'écran et à une main*. Il s'agit d'un vaste sujet de recherche et nous l'avons limité au cas des contrôles continus, et en particulier à l'interaction avec les curseurs sur des dispositifs mobiles. Le réglage de paramètres continus avec des curseurs sur les dispositifs mobiles est courant dans les environnements professionnels (par exemple, les ingénieurs du son fixant le volume sonore d'un lieu avant un concert et les scientifiques filtrant les données affichées sur un grand écran) mais aussi dans les environnements domestiques (par exemple, une personne à la maison ajustant le volume sonore de la télévision ou la couleur de la

lumière d'une lampe).

Dans ce contexte, la question de recherche que nous avons abordée est la suivante : comment améliorer l'interaction sans regarder l'écran et à une main avec un curseur sur un dispositif mobile. Afin de répondre à cette question, nous avons adopté une approche en deux étapes (voir Figure 6) :

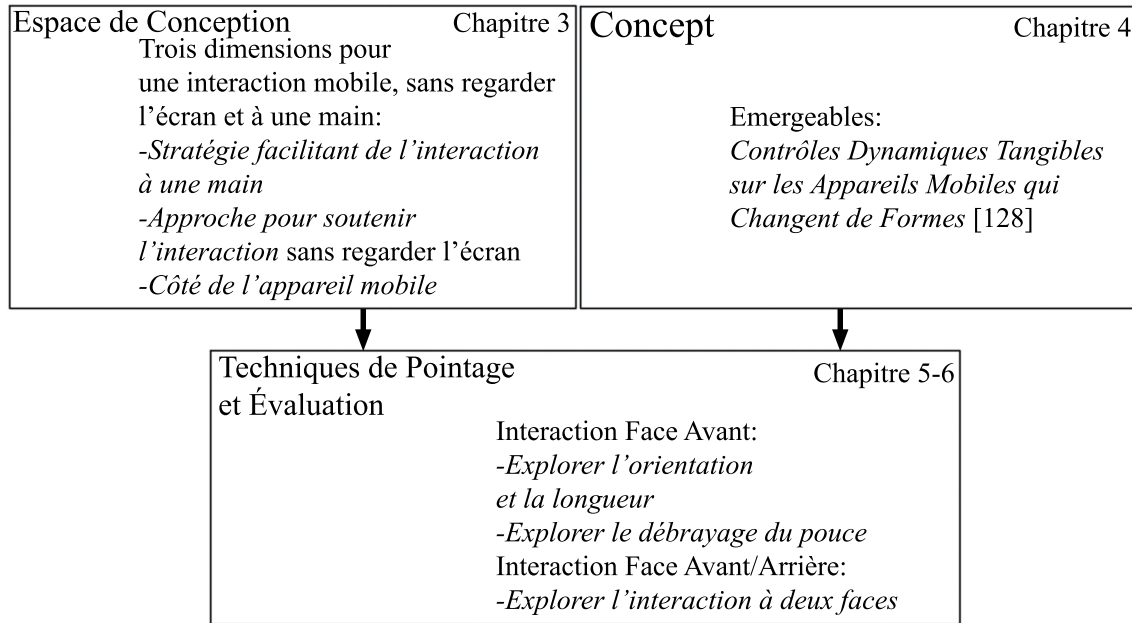


FIGURE 6 : Approche adoptée et résumé des contributions.

1. Nous avons établi un espace de conception (première contribution) basé sur notre analyse des techniques existantes pour l'interaction sans regarder l'écran et pour l'interaction à une main. L'espace de conception est structuré selon les caractéristiques que nous avons identifiées pour une interaction sans regarder l'écran et à une main. Nous décrivons également un concept d'interaction sans regarder l'écran avec des dispositifs mobiles appelé *Emergeables* [136] afin d'illustrer le dispositif mobile du futur qui pourrait prendre en charge de nouvelles techniques d'interaction sans regarder l'écran et à une main.
2. Basé sur notre espace de conception et le concept d'*Emergeables*[136]⁴, nous

⁴l'auteur de cette thèse faisait partie de l'équipe de recherche

avons conçu trois nouvelles techniques d'interaction sans regarder l'écran et à une main (deuxième contribution) que nous avons testées expérimentalement.

Ci-dessous, nous résumons nos contributions et présenterons ensuite les perspectives de ce travail.

Contributions

Nous contribuons à deux sous-domaines de l'Interaction Homme-Machine (IHM) (voir Figure 7) : l'interaction mobile et les interfaces tangibles qui changent de forme.

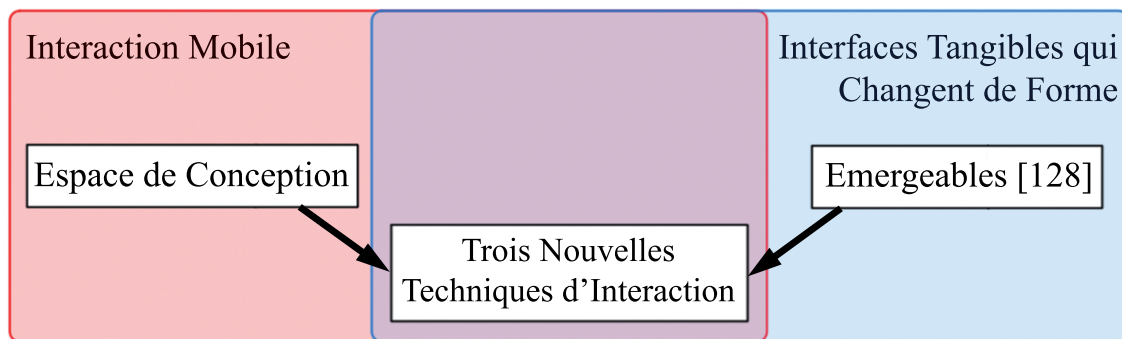


FIGURE 7 : Résumé des contributions et les sous-domaines d'IHM correspondants.

Espace de Conception

Nous avons établi un espace de conception pour une interaction sans regarder l'écran et à une main avec les dispositifs mobiles. L'espace de conception s'organise selon trois dimensions identifiées par une analyse des travaux existants dans la littérature : 1) la stratégie utilisée pour faciliter l'interaction à une main, 2) l'approche utilisée pour permettre une interaction sans regarder l'écran, et 3) le côté du dispositif mobile où l'interaction a lieu.

La première dimension fait référence à la *stratégie utilisée pour faciliter l'interaction à une main*. Deux stratégies sont identifiées le long de cette dimension :

- **Rapprocher les éléments près de la zone fonctionnelle du pouce** : Cette stratégie fait référence à des techniques qui consistent à déplacer l'interface par

des actions explicites (par exemple, inclinaison du dispositif mobile, gestes sur le bord de l'écran, bouton enfoncé) afin de rapprocher des zones inaccessibles dans la zone fonctionnelle du pouce.

- **Augmenter l'accessibilité du pouce** : Cette stratégie fait référence à des techniques utilisant des widgets graphiques (par exemple, des bâtons magnétiques) ou une autre modalité (par exemple, opération avec l'index à l'arrière du dispositif mobile) comme des extension de l'interaction avec le pouce pour atteindre des éléments extérieurs à la zone fonctionnelle du pouce.

La deuxième dimension fait référence à *l'approche utilisée pour permettre une interaction sans regarder l'écran*. Trois approches sont identifiées selon cette dimension :

- **Dans l'air** : cette approche repose sur des gestes corporels dans l'air (par exemple, déplacer la main de haut en bas, faire pivoter le pied) pour favoriser une interaction sans regarder l'écran.
- **Tactile** : Cette approche utilise des gestes sur la surface tactile du dispositif, tels que taper, glisser et incliner, pour interagir avec les dispositifs mobiles sans regarder l'écran.
- **Tangible** : Cette approche présente des éléments tangibles sur la surface du dispositif mobile pour permettre une interaction sans regarder l'écran.

La troisième dimension fait référence au *côté du dispositif mobile* sur lequel les actions sont effectuées. Trois surfaces principales sont identifiées : face avant, face arrière et côté du dispositif mobile.

L'espace de conception est élaboré à partir des caractéristiques de conception bien établies de la littérature existante pour une interaction sans regarder l'écran et à une main avec les dispositifs mobiles. La contribution clé de cet espace de conception réside dans son pouvoir de guider la conception de techniques d'interaction sans regarder l'écran et à une main, comme nous l'avons montré dans les Chapitre 5 et 6. Notre espace de conception constitue une première étape pour que les chercheurs explorent

de nouvelles techniques pour une interaction sans regarder l'écran et à une main avec des dispositifs mobiles.

Techniques d'Interaction Mobile sans Regarder l'Écran et À Une Main

Dans la littérature existante, nous avons constaté que les techniques à une main reposaient sur des interfaces graphiques. De telles solutions ne profitent pas des avantages des interfaces tangibles. Aussi en exploitant le concept d'*Emergeables* [136] de contrôles tangibles émergeant des surfaces d'un dispositif mobile, nous avons conçu trois techniques d'interaction basées sur notre espace de conception. Les techniques reposent sur des curseurs tangibles, qui changent de forme et qui sont capables de modifier différentes propriétés de conception (voir Figure 8).

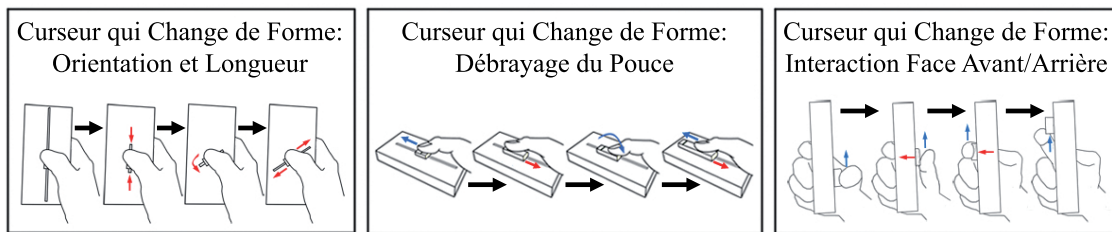


FIGURE 8 : Les trois techniques proposées : Gauche) Le changement de l'orientation et de longueur du curseur tangible pour l'adapter à la zone fonctionnelle du pouce ; Au milieu) Curseur tangible extensible permettant des mouvements de débrayage du pouce pour maintenir la manipulation dans la zone fonctionnelle du pouce ; Droite) Curseur tangible sur les deux faces permettant l'interaction avec l'index sur la face arrière pour atteindre des cibles en dehors de la zone fonctionnelle du pouce.

La première technique vise à faciliter l'interaction à une seule main en modifiant l'orientation et la longueur des curseurs. Dans une expérience contrôlée, quatre conceptions différentes de curseurs tangibles sont testées pour une tâche de pointage à distance : un grand curseur vertical, un grand curseur incliné, un petit curseur vertical et un petit curseur incliné. Les résultats montrent que : 1) l'orientation du curseur n'a aucune influence sur les performances, et 2) les petits curseurs ont des performances plus lentes par rapport aux curseurs plus grands en raison de la taille de l'espace moteur.

La seconde technique repose sur le débrayage du pouce sur un curseur tangible extensible pour faciliter l'interaction à une main tout en rendant possible l'interaction sans regarder l'écran. Dans une première expérience, il a été observé qu'un curseur tangible avec un très long bouton (prototype basse fidélité), qui permet le débrayage du pouce, est plus performant que la manipulation directe avec un curseur tangible classique. Pour une seconde expérience, nous avons construit et évalué un prototype tangible actionné par un moteur. Les résultats montrent que les performances du débrayage du pouce sur le prototype actionné dépassent celles du curseur graphique classique pour les cibles éloignées de la zone fonctionnelle du pouce. Cependant, le mouvement des moteurs perturbe l'interaction. Dans une troisième expérience, nous testons une nouvelle version du prototype tangible actionné avec une épaisseur réduite (-20mm). Nous avons ensuite étudié l'impact du mouvement des moteurs sur l'interaction sans regarder l'écran. Les résultats montrent que le prototype actionné fonctionne aussi bien en condition aveugle que non aveugle et ses performances dépassent celles d'un curseur extensible graphique.

La troisième technique propose une interaction sur les faces avant et arrière du dispositif avec un curseur tangible qui change de forme. Dans une première expérience, nous évaluons différentes transitions entre les faces avant et arrière. L'objectif est d'informer la conception pour faciliter le changement entre les faces avant et arrière. Les résultats montrent que les mouvements de déformation perpendiculaires au mouvement du pouce ne perturbent pas l'interaction et qu'une transition instantanée est préférable à une transition progressive. Dans une deuxième expérience, nous comparons l'interaction sur les deux faces (avant et arrière) avec l'interaction basée sur le débrayage du pouce et la manipulation directe dans le cas des cibles éloignées de la zone fonctionnelle du pouce. Les résultats montrent que les performances de l'interaction sur les deux faces dépassent les autres conditions tout en fournissant une prise en main stable. Dans une troisième expérience, nous évaluons les mêmes conditions mais pour atteindre des cibles proches de la portée du pouce. Les résultats montrent que, même si un curseur tangible conventionnel donne des meilleures performances que notre approche face avant/arrière, notre solution permet une prise en main stable.

Les conclusions des études réalisées sont les suivantes :

- L'utilisation d'un curseur long et tangible à l'avant d'un dispositif mobile est efficace pour acquérir des cibles sur des distances courtes (moins de 70mm environ). Cependant, une opération au-delà de ce seuil provoque des mouvements de la main (c'est-à-dire, changements de prise en main et déplacements du dispositif dans la main) qui peut être inconfortable et instable : une corrélation entre les changements de la prise en main et la perception de la sécurité (c'est-à-dire, risque de chute du dispositif) a été observé expérimentalement pour différentes postures corporelles [41]. De plus, les situations mobiles augmentent les mouvements du dispositif dans la main le tenant [13], qui pourrait éventuellement amener l'utilisateur à laisser tomber le dispositif.
- Améliorer l'accessibilité du pouce par le débrayage s'est révélé un moyen efficace pour acquérir des cibles sur des longues distances (environ 200 mm). Le débrayage du pouce sur des curseurs extensibles situés sur la face avant du dispositif mobile permet un fonctionnement avec de curseurs longs et évitant ainsi l'effet d'échelle présent sur les petits curseurs. De plus, les mouvements avec le pouce permettent également de d'interagir avec une prise en main stable.
- L'utilisation de l'interaction sur les deux faces avec le pouce et l'index constitue un moyen efficace d'acquérir des cibles sur des distances moyennes (environ 100 mm). L'interaction sur les deux faces surpasse la manipulation directe (-0,17s) avec un curseur tangible conventionnel, et permet également d'interagir avec une prise en main stable.
- La transition entre formes est un élément clé lors de la conception de contrôles qui changent automatiquement de forme lors de la manipulation. Nous avons observé que l'activation de la technique d'interaction sur les deux faces avait moins d'impact sur les performances (-0,83s) que celle de la technique de débrayage du pouce. Les deux solutions actionnées du chapitre 5 et du chapitre ?? diffèrent par l'orientation de la transition lors du changement de formes. Les participants ont

indiqué que le mouvement d’extension de la technique de débrayage du pouce était distrayante car le bouton du curseur était actionné dans le sens opposé du mouvement du pouce. Au contraire, un mouvement “morphing-in/out” comme celui de la technique face avant/arrière ne perturbe pas l’interaction sur un curseur actionné. Nous suggérons donc d’éviter une transition lors du changement de formes qui soit opposée à la direction du mouvement du pouce pour des contrôles tangibles actionnées avec le pouce.

- Les approches tangibles testées qui changent de forme (un curseur tangible extensible et un curseur tangible sur les deux faces du dispositif mobile) ne nécessitent pas l’attention visuelle de l’utilisateur pour être utilisées. Cela suggère que le mouvement des contrôles tangibles qui changent de forme, ne requièrent pas l’attention visuelle de l’utilisateurs lors de l’interaction.

Limitations

D’après les études réalisées, nous considérons que la mise en œuvre les prototypes pourraient être améliorés. Pour cela, nous considérons trois limites principales à traiter : l’actionnement, l’épaisseur et la friction des prototypes.

Vitesse et Bruit de l’Actionnement

La première limitation de nos études avec les curseurs était la vitesse d’actionnement. Les servomoteurs utilisés fonctionnaient à 130 tours par minute à 6 volts. Une telle vitesse n’est pas pu être optimale pour nos études expérimentales. Par exemple, nous avons observé que le temps de débrayage du pouce était plus lent avec les curseurs actionnés qu’avec le curseur long qui simulait un curseur déjà étendu. Nous considérons donc important d’identifier la vitesse minimale du pouce (Section 5.6) et ce pendant, l’interaction sur les deux faces (avant et arrière) (Section 6.4).

Afin de généraliser l’impact de la vitesse d’actionnement sur les performances, nous souhaitons évaluer d’autres dispositifs tangibles qui changent de forme. Par exemple, un bouton rotatif dont le diamètre et/ou la hauteur s’agrandit ou se réduit

en fonction du paramètre contrôlé [160].

Nous considérons également que le bruit d'actionnement pourrait avoir un impact sur l'interaction. Bien que les moteurs utilisés pour actionner les prototypes dans les chapitres 4, 5 et 6 (pages 73, 81 et 131) étaient bruyants, aucun des participants n'a commenté le bruit. Cependant, nous considérons qu'il est important d'évaluer si le bruit des actionneurs est utilisé comme retour d'information par les participants pour connaître l'état du curseur. Par exemple, lorsqu'ils soulèvent leur pouce du curseur tangible actionné, les participants attendent que le bruit d'activation se termine pour poser le pouce sur le curseur).

Épaisseur

La deuxième limite de nos études est liée à l'épaisseur des prototypes testés. Des études existantes ont montré que l'épaisseur d'un dispositif mobile pouvait non seulement affecter les performances de l'utilisateur dans une tâche de pointage [97], mais également affecter la façon dont les utilisateurs tiennent le dispositif avec une seule main [12]. L'épaisseur de nos prototypes allait de 20 mm (voir les sections 5.2, 5.6 et chapitre 6) à 40 mm (voir les sections 5.4 et 5.5). Bien que le marché actuel des smartphones propose des dispositifs d'une épaisseur maximale de 14,8 mm (par exemple, Trekker-M1 [37]), les dispositifs les plus modernes présentent une épaisseur de 7,7 mm (par exemple, iPhone X [4]). Nous considérons que nos prototypes tangibles, plus volumineux, pourraient forcer les participants à adopter des prises en main inconnues par rapport aux dispositifs mobiles commerciaux. Les actionneurs linéaires et les servomoteurs actuels présentent des dimensions qui limitent la conception de prototypes plus minces. Envisageant un avenir avec des actionneurs miniaturisés, nous aimerions réévaluer nos approches avec une telle technologie afin d'assurer dans nos études une prise en main plus proche de celles utilisées sur les dispositifs mobiles modernes.

Friction

La troisième limite liée à nos études est la friction des prototypes tangibles extensibles de la section 5.5 et 5.6. Les expériences effectuées dans ces sections se sont

concentrées sur les études de l'interaction loin de la zone fonctionnelle du pouce et, par conséquent, nécessitant des curseurs longs. Cependant, les curseurs commerciaux ne varient que de 15 mm à 100 mm. Nous avons ensuite construit, principalement avec une imprimante 3D, deux curseurs tangibles actionnés. La surface résultante des curseurs imprimés n'était pas complètement lisse. Afin d'améliorer le glissement du bouton du curseur, les surfaces ont été polies et nous avons utilisé du spray lubrifiant. Cependant, comparés aux curseurs graphiques affichés sur la surface lisse des écrans tactiles, la différence était perceptible. Trois participants à nos expériences de la section 5.5 et 5.6 ont commenté que la force initiale requise pour commencer à déplacer le curseur tangible était plus grande par rapport au curseur graphique. Malgré cela, l'attention visuelle requise par le curseur graphique a eu un impact plus important sur l'interaction. Néanmoins, nous considérons que la friction est un paramètre pertinent à prendre en compte lors de la mise en œuvre de curseurs tangibles.

Perspectives

Nous identifions plusieurs directions de recherche à nos travaux. Nous les présenterons en deux catégories : les perspectives à court terme et celles à long terme.

Perspectives à Court Terme

Exploration de la Phase de Changement de Forme : Nous avons observé expérimentalement que l'orientation du mouvement des curseurs actionnés pouvait avoir un impact sur l'interaction (Section 5.1). Un curseur actionné avec un mouvement d'extension dans le sens opposé au mouvement du pouce a eu un effet négatif sur les performances (Section 5.3). Au contraire, aucun impact sur les performances n'a été observé avec un mouvement du curseur perpendiculaire au mouvement du pouce (chapitre 6). Ceci est une observation très importante pour la conception de toute interface dont le changement de forme est contrôlée par le système [134]. Aussi nous souhaitons explorer plus avant l'impact des différentes propriétés (par exemple, l'orientation, la forme, le volume, la texture) d'une interface tangible qui change de

forme sur l'interaction lors de la phase de changement. Par exemple, nous souhaitons évaluer l'impact du changement de volume (c'est-à-dire la hauteur, la largeur et l'épaisseur) du bouton d'un curseur sur l'interaction pendant sa manipulation. Cette voie de recherche peut être étendue à l'étude d'autres contrôles tangibles qui changent de forme, telles que les molettes rotatives actionnées [160].

Parce que nous avons étudié les commandes tangibles qui changent de forme et qui sont manipulées par les utilisateurs, la phase de changement est cruciale. Cela ouvre une voie de recherche sous-explorée dans le domaine des interfaces qui changent de forme [46, 59, 61, 65, 163, 139, 133, 185].

Exploration de Plusieurs Contrôles qui Changent de Forme : Nous souhaitons également étudier l'interaction avec de multiples curseurs tangibles qui changent de forme dans le contexte du réglage de différents paramètres continus (par exemple, le contrôle des niveaux RGB d'un projecteur). Une telle étude combinerait les avantages des widgets tangibles apparaissant à la demande (le concept d'*Emergeables* [136], voir la Section 4) et les avantages des contrôles tangibles qui changent de forme pour une interaction sans regarder l'écran et à une main (voir les sections 5 et 6). Nous sommes particulièrement intéressés par les défis qu'implique la manipulation de plusieurs contrôles tangibles avec une seule main. Par exemple, étudier la transition de forme lors du changement d'opération d'un contrôle tangible à un autre afin d'éviter des opérations accidentelles sur d'autres contrôles tangibles.

Explorer la Face Latérale d'un Dispositif Mobile : Comme décrit dans l'espace de conception, la face latérale des dispositifs mobiles peut servir d'entrée complémentaire (comme la face arrière dans la technique d'interaction du chapitre 6) pour faciliter l'interaction au pouce sur la face avant. Dans la section 3.2, nous avons décrit les travaux existants qui utilisent une interaction tangible sur la face latérale des dispositifs mobiles. Cependant, ces techniques n'ont pas été conçues pour faciliter les interactions à une main. Nous voulons étudier comment la face latérale pourrait être exploitée pour une interaction avec des contrôles continus. Par exemple, nous aimerions évaluer

les performances d'un curseur situé sur la face latérale d'un dispositif mobile que les utilisateurs pourraient utiliser avec les doigts disponibles pour atteindre des cibles situées en dehors de la zone fonctionnelle du pouce. De plus, nous souhaitons étudier la zone fonctionnelle des doigts sur la face latérale afin d'informer la conception de nouvelles techniques d'interaction.

Validité Écologique : Afin de prolonger la validité de nos études, nous aimerions tester plus avant nos approches avec des utilisateurs cibles [176] de curseurs, tels que les ingénieurs du son. En effet, le travail présenté dans cette thèse était fortement inspiré par les besoins de ces professionnels dans leur environnement de travail. Comme les ingénieurs du son utilisent des curseurs tangibles de différentes manières (par exemple, en utilisant deux doigts dans un geste pincé ou en utilisant un seul doigt), nous envisageons d'évaluer si les techniques d'interaction proposées (c'est-à-dire le débrayage du pouce et l'interaction sur les deux faces) avec ces utilisateurs. Nous considérons que l'évaluation, tant qualitative que quantitative, de nos techniques par ces utilisateurs principaux est très pertinente et pourrait conduire aussi à de nouvelles techniques d'interaction.

Perspectives à Long Terme

Conception Réactive pour les Interfaces Tangibles qui Changent de Forme :

Le concept d'*Emergeables* [136], présenté dans le chapitre 4, repose sur des dispositifs mobiles qui changent de forme, capables de faire apparaître des contrôles tangibles sur la surface afin de permettre une interaction sans regarder l'écran. Un tel concept pose la question de la conception des interfaces tangibles : les directives de conception des interfaces graphiques sont-elles suffisantes pour la conception des interfaces tangibles ? Nous considérons que ceci est hautement improbable. Par exemple, les curseurs graphiques sur les dispositifs mobiles dotés du système d'exploitation Android présentent une taille de bouton de 12 pixels (environ 4 mm) [53], alors que les instructions de conception des boutons de curseurs tangibles recommandent une taille d'au moins 10 mm [93]. Par conséquent, les interfaces tangibles contiendront proba-

blement moins d'éléments que les interfaces graphiques afin de maintenir l'interface opérationnelle.

De plus, dans le chapitre 5, nous avons imaginé des contrôles tangibles qui non seulement émergent de la surface du dispositif mobile, mais aussi peuvent également changer de forme afin de faciliter les interactions à une main. De tels contrôles tangibles qui changent de forme soulèvent le problème de la disposition de l'interface lorsque des contrôles tangibles changent de forme. Par exemple, un cadran rotatif qui augmente son diamètre au sein d'une interface composée d'autres éléments tels que des icônes, du texte et des boutons. Actuellement, le responsive web design [111] est une approche qui substitue les dispositions statiques par des dispositions flexibles permettant un placement relatif des éléments de l'interface en fonction de la taille de l'écran du dispositif mobile. De cette manière, les interfaces de sites Web peuvent s'adapter pour s'ajuster à la taille de l'écran et faciliter la navigation sur différentes tailles d'écran. Nous considérons cette approche comme une solution possible pour résoudre le problème des interfaces comprenant des contrôles tangibles qui changent de forme. Les travaux futurs dans le cadre d'une telle approche pourraient aboutir à des directives de conception pour une conception réactive des interfaces tangibles qui changent de forme, et par là-même pourrait probablement réduire l'écart entre la conception d'interfaces graphiques et tangibles.

Du Graphique au Tangible et Vice-versa : Le concept d'*Emergeables* [136] présenté dans le chapitre 4 désigne des dispositifs mobiles qui changent de forme : les contrôles graphiques affichées sur l'écran peuvent "se transformer" pour aboutir à une version tangible. De tels dispositifs mobiles qui changent de forme afficheront des contrôles graphiques (par exemple, des boutons, des curseurs et des cadrans rotatifs) lorsque l'utilisateur regarde l'écran. Lorsque l'utilisateur déplace son attention visuelle de son dispositif, les contrôles graphiques deviennent alors des contrôles tangibles. Cependant, il n'est pas clair de quelle manière la transition du graphique au tangible devrait être commencée afin de ne pas perturber l'interaction.

Des études existantes (par exemple, [88, 91, 185]) et les travaux présentés aux

chapitre 5 et au 6 considère le cas où c'est l'utilisateur qui déclenche la transition de changement de forme, à savoir *changement de forme directement contrôlé* [135]. Cependant, une telle approche peut perturber l'interaction [88, 91]. Il est donc nécessaire d'explorer d'autres approches. En plus de *changement de forme directement contrôlé*, Rasmussen *et al.* [135] propose trois autres approches : *changement de forme indirectement contrôlé*, *changement de forme contrôlé par le système* et *changement de forme négocié*. Compte tenu de ces approches, la question qui se pose est la suivante : quelle approche de transition minimise la perturbation de l'interaction ?

De plus, ces contrôles tangibles peuvent également changer de taille (par exemple, hauteur et largeur), entraînant une adaptation de l'interface. Cela pourrait entraîner la suppression d'autres éléments de l'interface afin de libérer l'espace requis par le contrôle tangible redimensionné.

Enfin, lorsque l'utilisateur regarde à nouveau à l'écran du dispositif mobile, plusieurs solutions doivent être étudiées : le contrôle tangible doit-il revenir à une version graphique ? et si oui, le dispositif mobile doit-il conserver la nouvelle disposition d'interface ou revenir à la précédente ?

Perspectives à Très Long Terme

Des curseurs tangibles pourraient être bénéfiques pour une interaction à une main sur les applications mobiles actuelles qui utilisent des curseurs pour contrôler des paramètres continus. Par exemple, lors du réglage de la luminosité de l'écran, le pouce de l'utilisateur peut facilement s'éloigner du bouton de curseur puisque son mouvement suit une trajectoire parabolique [13]. Envisageant un dispositif mobile qui change de forme et capable de rendre tangible le bouton du curseur, l'utilisateur pouvait alors percevoir le cas où son pouce s'éloigne. L'utilisateur peut alors réajuster sa prise en main pour éviter d'arrêter de manipuler le curseur tangible. Une telle solution pourrait être très bénéfique dans les situations où l'utilisateur contrôle un système distant avec un dispositif mobile. Par exemple, un dispositif mobile qui change de forme et capable de rendre des curseurs tangibles pour l'application Philips Hue [130]. Les utilisateurs seraient alors en mesure de changer différents paramètres de couleur d'une

lampe dans une pièce sans regarder le dispositif pour changer le fonctionnement d'un curseur à l'autre.

Un autre exemple courant de curseurs sur des dispositifs mobiles réside dans les barres de défilement pour une exploration rapide d'un document ou d'un site Web. Ces curseurs sont généralement situés sur le bord droit de l'écran. Étant donné que les prises en main sur des dispositifs mobiles permettent généralement une utilisation confortable du pouce au centre de l'écran [85], l'interaction avec les barres de défilement peut être inconfortable. Pour de telles situations, nous envisageons que notre curseur tangible sur les deux faces (avant et arrière) pourrait faciliter l'interaction à une main. Les utilisateurs peuvent déclencher le bouton tangible sur la face avant du dispositif n'importe où sur l'affichage par un geste, par exemple, une pression sur l'écran. Le geste déclencherait alors l'apparition d'un bouton tangible situé sous la position du pouce de l'utilisateur. De cette manière, l'utilisateur pourrait invoquer le curseur tangible à l'endroit le plus confortable pour le pouce et index.

En ce qui concerne un curseur tangible sur les deux faces (avant et arrière), une telle technique d'interaction ne serait pas disponible si le dispositif mobile était recouvert d'un étui de protection. Puisque nous envisageons un dispositif mobile qui change de forme dont le dos est totalement interactif et déformable, nous nous attendons à ce que les étuis de protection laisseraient la face arrière non recouverte afin de permettre une interaction sur la face arrière du dispositif.

Appendix A

Sound Engineer Survey

Survey for sound engineers

*Required

Do you find yourself in situations where you need to control sound parameters (e.g. volume, pan) while being away from the mixing console? *

- yes
 no
 Other: _____

If yes, please describe a common situation where you need to be mobile *

1. Small spaces where there is nowhere sensible to put a mixer out front
 2. Setting monitor mixes from on the stage
 3. When I want to hear how it sounds in another part of the room
 4. When I'm using a desk with no (or limited) physical controls on it.
- _____

Do you find yourself in situations where you need to look away from the controls while you are operating them? *

- yes
 no
 Other: _____

If yes, please describe a common situation where you need to be eyes-free *

Taking visual cues from the band usually

Do you find yourself in situations where you need both to be eyes-free and mobile while controlling sound parameters?

- yes
 no
 Other: _____

Figure A.1: Example of a participant's answers to the survey for sound engineers used for the case scenario of page 33.

Appendix B

System Usability Scale

System Usability Scale

© Digital Equipment Corporation, 1986.

	Strongly disagree				Strongly agree
1. I think that I would like to use this system frequently	1	2	3	4	5
2. I found the system unnecessarily complex	1	2	3	4	5
3. I thought the system was easy to use	1	2	3	4	5
4. I think that I would need the support of a technical person to be able to use this system	1	2	3	4	5
5. I found the various functions in this system were well integrated	1	2	3	4	5
6. I thought there was too much inconsistency in this system	1	2	3	4	5
7. I would imagine that most people would learn to use this system very quickly	1	2	3	4	5
8. I found the system very cumbersome to use	1	2	3	4	5
9. I felt very confident using the system	1	2	3	4	5
10. I needed to learn a lot of things before I could get going with this system	1	2	3	4	5

Figure B.1: Example of a participant's answers to the SUS (System Usability Scale) questionnaire an experiment 2 (page 84). This questionnaire was used on the experiments from Section 5.2, 5.4, 5.5, 5.6 and 6.5.

Appendix C

Emergeables, Dynamic Tangible Controls on Shape-Changing Mobile Devices

In order to demonstrate and test the potential of *Emergeables*, two emergeable prototypes were built: 1) a high-resolution prototype, where controls appear on the surface in a set of fixed positions; and 2) a low-resolution prototype that uses a rod-based widget model to render lower-resolution controls, which provide flexibility in positioning. We aim at addressing the following research questions:

- Does the *Emergeables* concept have a lower impact on the performance and on the required visual attention when manipulating continuous controls (i.e. dials and sliders) than a graphical user interface?
- Will such an ambitious end-goal (i.e. shape-changing mobile devices) provide sufficient benefits given the costs related with its development?

The two main contributions of this experiment are the following:

- The quantification of the benefits that emergeables has on performance time, accuracy, and eyes-free interaction.

- Design insights for rod-based control widget models based on qualitative user experience observations.

We want to clarify that the author of this thesis was not the main author of the *Emergeables* concept. However, he was part of the research team in which he designed and developed the high-resolution prototype, and was also involved in the analysis of the collected data from the experiment.

C.1 Prototypes

We built two emergeable prototypes with different levels of resolution. We did this in order to demonstrate the *Emergeables* concept and test its potential (see Figure C.1). The first prototype is a low-resolution emergeable device, inspired by the Pinscreen¹ toys, and existing research implementations, such as [47]. Each sensel (15mm) can be translated up to 15 mm in any direction, or be fully rotated. The second prototype is a high-resolution emergeable device, built for the predefined tasks of our experiment, that raises real tangible controls on-demand. This prototype allowed us to explore the benefits of high-resolution future emergeables. We built this high-resolution prototype while our co-authors built the low-resolution one.

C.1.1 Low-Resolution Prototype

The low-resolution prototype (see Figure C.1, A) is composed of circular sensels (15 mm diameter) arranged in an array of 4×7 . Each sensel moves independently (powered by a micro stepper motor), and can be raised and lowered up to 15 mm. Each sensel can also be manipulated by the user in three ways: pushing (as a button); rotating (as a dial); and, tilting to simulate a limited translation (15 mm in any direction), which is used to create sliders in conjunction with contiguous sensels (see Figure C.2). Sensels are surrounded by a bristle mesh that fills gaps as they are moved during manipulation (see Figure C.1, B). With these features, it is possible to

¹See pinscreens.net (also known as Pinpression).

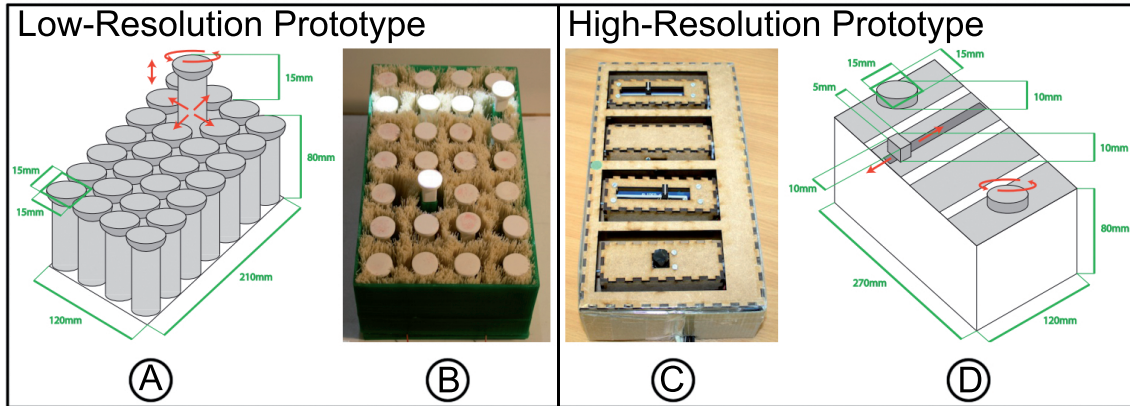


Figure C.1: (A) the design of the low-resolution prototype. Each sensel of the device can be rotated as a dial and tilted vertically or horizontally to form part of a slider. (B) the low-resolution prototype, with a raised slider (top) and dial (bottom). See Figure C.2 for an illustration of using the prototype. (C) the high-resolution prototype. The box is formed by four rotatable panels, each capable of switching between flat surface, dial or slider. (D) the design of the high-resolution prototype. Figure from [136].

emerge a dial or slider in any location on the prototype’s surface, and remove it when not required.

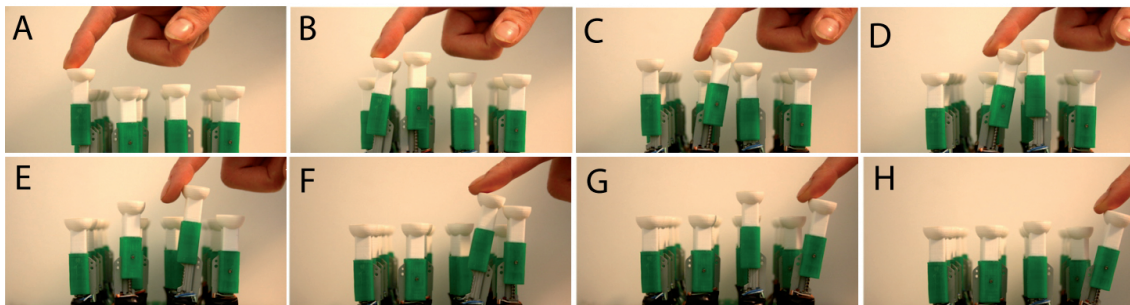


Figure C.2: Interaction with a slider on the low-resolution prototype: first, a single sensel emerges at the slider thumb’s current position (image A). Then, the user can tilt this and each adjacent sensel in succession to simulate movement along the slider’s path (images B–H). Figure from [136].

To render a dial, a single sensel is raised for the user to turn. To render a slider, one sensel is raised – when this sensel is tilted, the next sensel along the line of the slider is raised, and the movement continues. In this way, it is possible to simulate fluid interaction with a slider via tilting alone (see Figure C.2). Although this current version has relatively large sensels, we believe this approach could in future be greatly

miniaturised.

C.1.2 High-Resolution Prototype

The high-resolution prototype (see Figure C.1, C) is made of actual dials and sliders that can be shown when needed by rotating a panel on its surface. The prototype consists of four rotatable panels, each of which is controlled by a separate rotational servomotor, allowing it to display either a slider, dial or flat surface (mimicking the ‘un-emerged’ display) in each position (see Figure C.3).

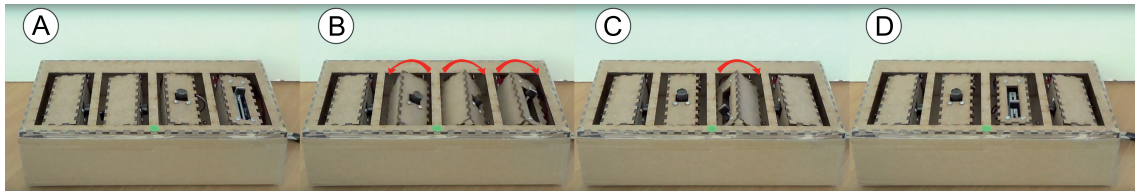


Figure C.3: The high-resolution prototype is composed of four rotatable panels, allowing it to display either a slider, dial or flat surface. The rotation of the panels simulate the displacement of the tangible controls along the surface (images A–D). Figure from [136].

C.2 Experiment

We conducted an experiment in order to evaluate the impact of resolution on performance and the required visual attention with mobile continuous controls. We focus on dials and sliders, as they provide a continuous adjustment of a parameter. Our goal is to quantify the performance benefits of, and obtain qualitative user experience insights into, the concept of emergeables. Our motivation is to consider if such an ambitious end-goal will provide enough benefits given the costs associated with its development.

In addition to the two emergeable prototypes, our co-authors created a non-emergeable touch-screen interface for comparison (developed on an Android tablet), which displayed standard platform dials and sliders in the same positions and at the

same sizes as the two physical prototypes (see Figure C.4). The size, input resolution, location and latency of each widget was the same between all three designs.

C.2.1 Method

The experiment followed a within-subject design with three independent variables:

- **Resolution:** GUI, low-resolution emergeable or high-resolution emergeable;
- **Complexity:** 1 or 2 widgets (controlled simultaneously);
- **Widget:** Dial or slider.

The order of presentation of the *Resolution* conditions was counterbalanced across participants using a latin square design. The *Complexity* variable was presented in increasing order. Finally, the order of presentation of the *Widget* conditions were randomised. For instance, participant 1 was presented with the following sequence: single slider, single dial, two dials, two sliders, dial and slider; and, used each widget first with the GUI, followed by the high-resolution and then the low-resolution prototypes. In all cases, the physical location of the widgets was randomised between one of four positions (see Figure C.1, C.4, and C.6).

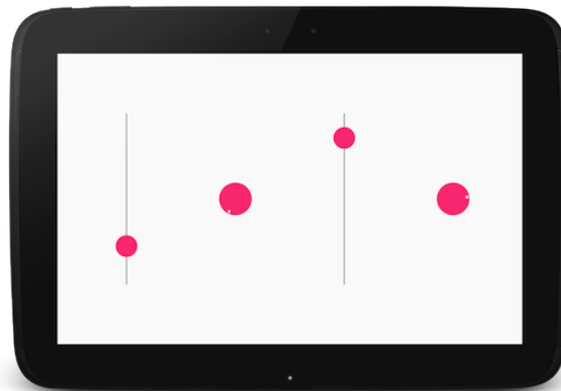


Figure C.4: The graphical interface used for comparison in the experiment. A widget is shown in each of the four positions used (only two of these positions were used at any one time in the study – see Figure C.6). Figure from [136].

C.2.2 Tasks

To simulate mobility and users switching between continuous control tasks, the study involved participants using the prototypes to control graphical controls (i.e. dials and sliders) projected on two separate screens either side of the participant's location (see Figure C.5).

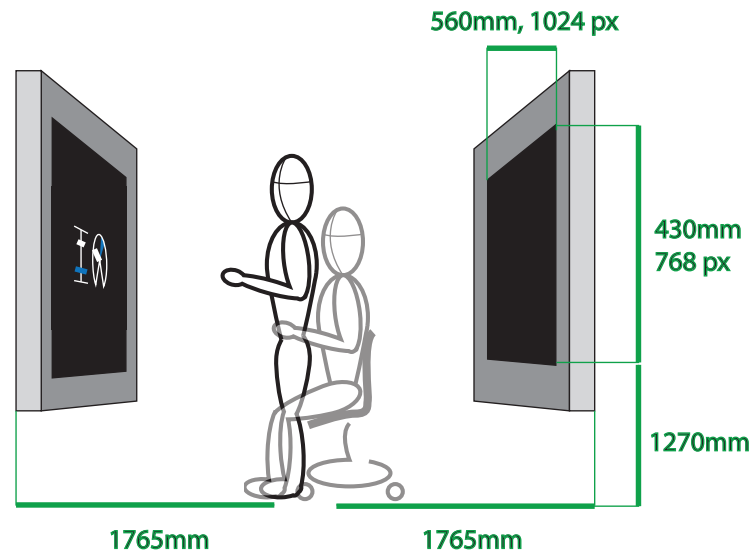


Figure C.5: Experimental setting: participants were positioned between two projected screens, and used each of the prototypes in turn to perform a pursuit task with sliders and dials (see Figure C.6). The task swapped between the two screens every 15 seconds, and participants performed the task for 60 seconds at a time. When using a single control, participants stood; for two controls participants were seated (to allow both hands to be used at the same time). Figure from [136].

As in previous work on continuous parameter adjustment (e.g., [81, 45]), the task required participants to pursuit a target cursor along either a linear (slider) or circular control (dial). We chose this type of task as many higher-level human actions depend on this one-dimensional pursuit method (e.g., [81]). Figure C.6 shows the graphical version of both the slider (left) and dial (right) pursuit tasks at their four possible locations on the display. In each case, the current position of the cursor is shown as a thick white line, and the target area is in blue. Participants were asked to keep the white line within the blue target area at all times.

As in [81], the target moved at constant speed and darted off at pseudo-random

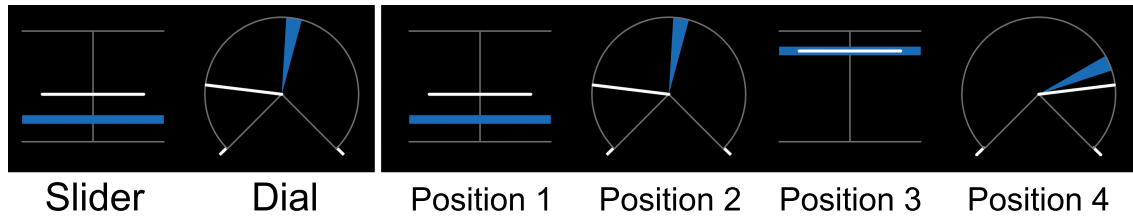


Figure C.6: An example of the display the user saw on the projected screen while carrying out the pursuit task. In this example, two widgets on the emergeable are used to control the slider and dial (left). There are four positions in which controls could be displayed (right). Only one (single widget task) or two (dual widget task) widgets were visible at any one time. The widgets on each prototype were presented in the same positions relative to the large screen. Solid white lines are the user's controller in each case; blue shaded areas are the target. Figure from [136].

intervals (2s to 4s). The full projected size (S) of each control was 20 cm; the speed was $0.15 \times S$, and the dart-off distance was $0.25 \times S$. Every 15 seconds, the projected control changed to the other screen. Participants were prompted by on-screen instructions to turn around, simulating a change in focus or application. This was repeated four times (e.g., 60 s total), after which participants were able to take a short break. With one-widget Complexity, participants performed a second iteration of 4×15 s tasks. With two-widget Complexity only a single iteration was performed.

When the task moved between screens, the location of the widget(s) changed randomly (consistently on both the projected screen and the prototype they were holding). As a consequence, participants needed to reacquire the control(s). This task design allowed us to take the change of focus or application into account in our study, and measure the impact of this change onto the interaction. In the case of the two-widget complexity, each target moved independently, and participants were required to control both widgets at the same time. Participants stood between the two display screens for the single widget task, and for two widgets they sat (to allow both hands to be used at the same time).

C.2.3 Procedure

We recruited 18 participants (18-66 years old, 9 male, 9 female) to take part in the experiments. All except one of the participants had at least two years' experience with touchscreens (the remaining participant had no experience), and four were left-handed. Sessions lasted, on average, 50 min.

After a discussion of the experiment and obtaining ethical consent, each experiment began with a short demographic questionnaire, including questions about the participant's preference for physical or digital interaction with buttons, sliders and dials. Afterwards, we showed the participant a short video of concept designs illustrating our intended use of the system. The participants were then given training with each of the prototypes, first using a slider on each (GUI, low-resolution, high-resolution), then a dial in the same order.

Participants then performed the series of tasks according to the experimental design previously described. In cases where there was only one widget to control, participants were asked to stand up holding the prototype with one hand while controlling the widget with the other. In cases where there were two widgets to control, we allowed the participant to sit in a swivel-chair with the prototype on their lap (to free up both hands for controlling the widgets). In both cases, participants were free to move their entire body (or body and chair) to face the appropriate screen where the task was being displayed.

The participants' accuracy for each task was captured in software, and all tasks were video-recorded to allow analysis of participants' head direction as a proxy for visual attention. The study ended with a short structured interview in which we asked about the participants' views on each interface. Participants were given a £10 gift voucher in return for their time.

C.2.4 Measures

The main objective of this study is to determine the effect of resolution on performance. To this end, we recorded – via logs – the accuracy of each participant's tasks

(i.e. how well they were able to follow the blue target region using the controls given). The accuracy was computed for each frame as the distance between the center of the cursor and the center of the blue target area. The accuracy was then aggregated for each participant using the geometric mean (giving a better indicator of location than the arithmetic mean, as the distribution of the error is skewed). In the case of two widgets, the accuracy was computed as the geometric mean of the accuracy of both widgets.

In addition, we also want to determine the level of visual attention required to operate each prototype (i.e. how often the user needed to look down at the device while controlling the projected widget(s)). To this end, we analysed each study’s video footage using ELAN [146], recording points where the user’s head direction moved from the projected screen to the physical device and the time spent looking at the controls.

Finally, as an indication of participants’ perceived usability of the prototypes, we asked them to rate each prototype out of 10 for how easy they found it to use (10 easiest). Participants were also asked to rank the prototypes in order of the required visual attention to operate them.

C.3 Results

C.3.1 Pre-Study Questionnaire

The results from the pre-study questionnaire mirror previous work in this area (see Section 3.1.3, page 54), showing that most of the participants prefer physical widgets over digital ones. Of the 17 participants that could answer this question², 13 of 17 preferred physical buttons, 9 of 17 preferred physical sliders, and 15 of 17 preferred physical dials. Participants stated that this preference is due to the precision that is afforded by, and the “feel” of, the physical controls. One participants even described the poor migration of physical widgets on their digital representations, stating “[...]”

²The participant with no touch screen experience did not respond.

graphical widgets are only attempts to imitate the real thing – they try and give the same experience but in a format that fits in your pocket”.

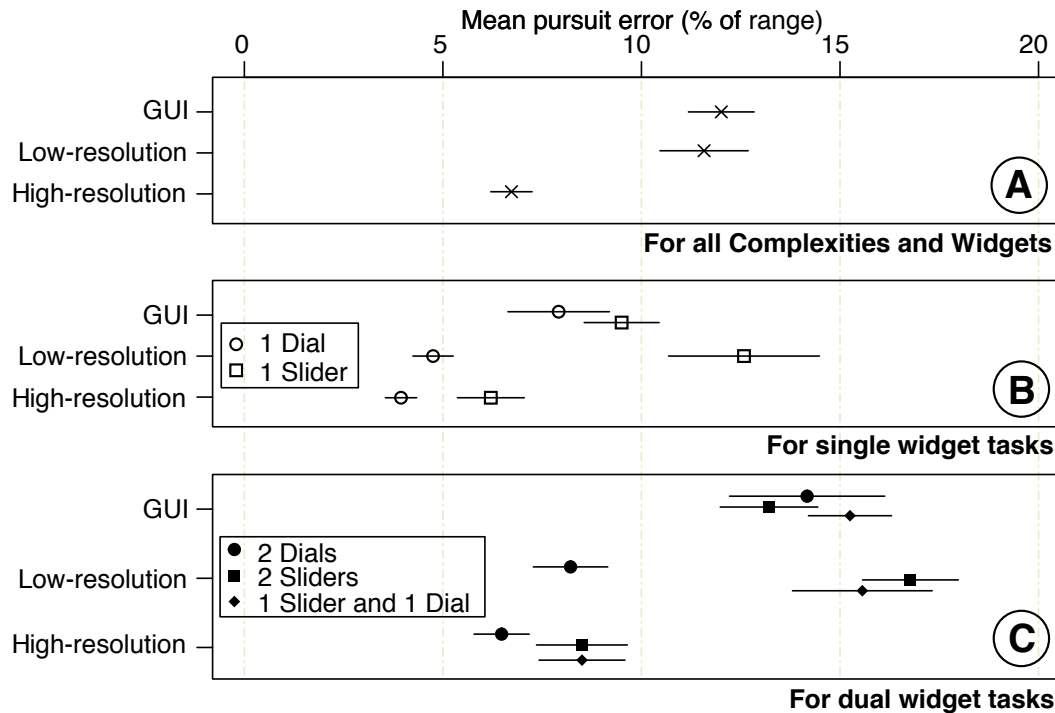


Figure C.7: Mean pursuit error as a percentage of control range. Error bars show 95% confidence intervals. Figure from [136].

C.3.2 Pursuit Accuracy

Figure C.7 shows the mean pursuit error (in percentage of the whole widget’s range), for each combination of Resolution, Widget and Complexity, aggregated over all tasks.

Overall (see Figure C.7, A), the high-resolution prototype led to 6.7% of pursuit error, and the low-resolution and GUI prototypes to 11.6% and 12.0% of pursuit error respectively. The high-resolution prototype was the most accurate. Both the low-resolution and GUI designs presented a similar accuracy level.

In order to further explain the differences between the prototypes, and understand the performance of the low-resolution emergeable prototype, we analysed the results for one and two widgets separately (see Figure C.7, B and C).

C.3.2.1 Single Widget Task

A two-way ANOVA shows a significant effect of Resolution ($F(2, 102) = 27.671, p < 0.001$) and Widget ($F(1, 102) = 72.308, p < 0.001$) on the pursuit error. A significant interaction between Resolution and Widget ($F(2, 102) = 18.674, p < 0.001$) was also found.

For the single slider task, comparisons using paired t-tests with Bonferroni corrections revealed significant differences between the low-resolution and GUI ($p < 0.01$), and between high-resolution and GUI, and low-resolution and high-resolution prototypes (both $p < 0.001$). The low-resolution prototype's slider led to 12.6% of pursuit error, the high-resolution slider led to 6.2%, and the GUI slider to 9.5%.

For the single dial task, the same comparison method revealed significant differences between the high-resolution and GUI, low-resolution and GUI, and between low-resolution and high-resolution prototypes (all $p < 0.001$). The high-resolution and low-resolution prototypes' dials led to 4.8% and 4.0% of pursuit error respectively, whereas the GUI dial led to 7.9% of the error.

C.3.2.2 Two-Widget Tasks

A two-way ANOVA shows a significant effect of Resolution ($F(2, 153) = 85.954, p < 0.001$) and Widget ($F(2, 153) = 26.270, p < 0.001$) on the pursuit error. A significant interaction of Resolution and Widget ($F(4, 153) = 14.716, p < 0.001$) was also found.

For the dual slider task, comparisons using paired t-tests with Bonferroni corrections revealed significant differences between the low-resolution and GUI ($p < 0.01$), and between high-resolution and GUI, and low-resolution and high-resolution prototypes (both $p < 0.001$). The low-resolution dual slider prototype led to 16.8% of the pursuit error, the high-resolution sliders led to 8.5%, and the GUI sliders to 13.2%.

For the dual dial task (see Figure C.7, C), the same comparison method revealed significant differences between the high-resolution and GUI, low-resolution and GUI, and between low-resolution and high-resolution prototypes (all $p < 0.001$). The low-resolution and high-resolution prototypes' dual dials led to 8.2% and 6.5% of the

pursuit error respectively, and the GUI dual dial led to 14.2 % of the error.

For the both slider and dial, the same comparison method revealed significant differences between the high-resolution and GUI, and between the low-resolution and high-resolution prototypes (both $p < 0.001$). However, no significant difference was found between the low-resolution and GUI prototypes. The low-resolution and GUI prototypes' dial and slider controls simultaneously led to 15.6 % and 15.3 % of the pursuit error, respectively, whereas the high-resolution dial and slider led to 8.5 % of the error.

C.3.2.3 Reacquiring Controls After a Change of Focus

After switching between targets, there is a period of time at the beginning of each task in which the participant needs to reacquire the control, due to it switching to a different position on the device and display. Overall, the GUI and low-resolution sliders take the most time for users to catch up with the target, and thus impacting the respective mean pursuit error. On average, with one widget, it took 4.7s to reacquire a low-resolution/high-resolution dial, and a high-resolution slider, and 5.9s with a low-resolution slider or either of the GUI widgets. On average, with two widgets, it took 5.9s to reacquire a low-resolution or high-resolution dial, or a high-resolution slider, whereas it took 6.9s with a low-resolution slider or either of the GUI widgets.

C.3.3 Glance Rate

One of the metrics we consider vital to the use of mobile devices for eyes-free interaction is the visual attention required to use the controller. To measure this, we systematically analysed the video footage from each participant's tasks, annotating every gaze deviation from one of the projected screens to the controlling device. We also recorded the time spent looking down, as shown in Figure C.8. Although the overall time spent looking down is an interesting metric, we focus mainly on the number of times the user glanced down. As participants tend to look down to reacquire a control, we believe this provides an accurate measure of the number of times the user

loses control of a particular widget, as opposed to how long it takes to reacquire it.

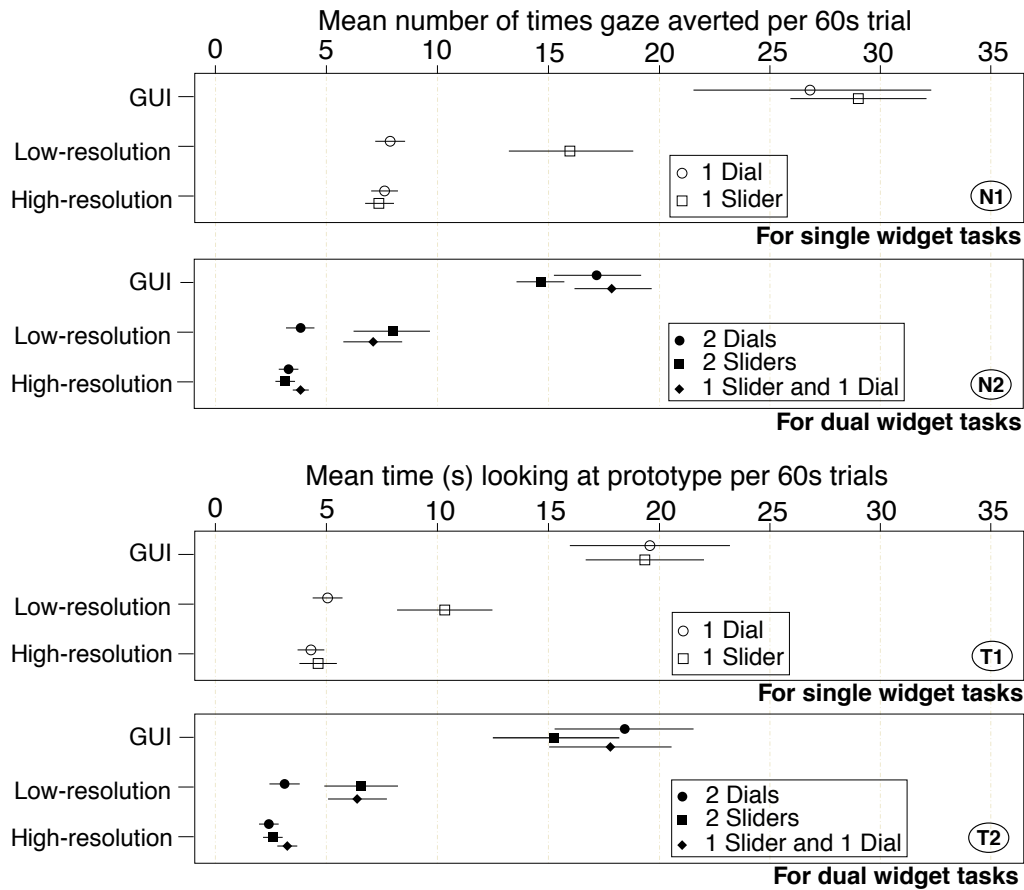


Figure C.8: Glance rates. Top: mean number of times participants' gaze was averted from the projected screen. Bottom: the mean time participants spent looking at the prototype (rather than the display) per trial. Figure from [136].

C.3.3.1 Single Widget Task

A two-way ANOVA on the glance data (i.e. glance rate and duration) shows a significant effect of Resolution ($F(2, 102) = 106, p < 0.0001$), indicating that the high-resolution prototype requires a lower glance rate than the GUI. The effect of the type of Widget was also significant on the glance rate ($F(1, 102) = 8.34, p < 0.05$), as was the interaction of Widget and Resolution ($F(2, 102) = 4.7, p < 0.05$). Paired t-tests with Bonferroni corrections found no significant differences between sliders and dials on the high-resolution or GUI prototypes. A significant difference was found between

sliders and dials on the low-resolution prototype ($p < 0.0001, t = 6.29, df = 17$). This shows that sliders on the low-resolution prototype require more visual attention than dials when performing a single widget task.

C.3.3.2 Dual Widget Task

A two-way ANOVA showed significant results for the effects of Resolution ($F(2, 153) = 383, p < 0.0001$) and Widgets ($F(2, 153) = 4.8, p = 0.01$) on visual attention. Moreover, the interaction between Resolution and Widgets was also significant ($F(4, 153) = 8.16, p < 0.0001$). This shows that, as with the single widget complexity, the high-resolution prototype requires the least visual attention, followed by the low-resolution prototype, and finally the GUI prototype. Post-hoc tests indicated significant differences between sliders, dials, and slider and dial simultaneously, indicating that, overall, the slider and dial task required greater visual attention than other dual-widget tasks. We argue that this is due to the different actions required to operate the widgets, i.e., sliding and rotating. For the low-resolution prototype, two dials required less visual attention than dual sliders; conversely, two sliders required less visual attention than two dials on the GUI prototype.

C.3.4 Subjective Results and Observations

Regarding the ease of use of each prototype, the given ratings (out of 10) resulted in average scores of 8.8, 4.8 and 3.4 for the high-resolution, low-resolution and GUI prototypes respectively. A Friedman test on these results shows the difference to be statistically significant ($p < 0.0001, df = 2$). These results confirm that participants found the high-resolution prototype the easiest to use, the touchscreen GUI the most difficult, and the low-resolution prototype somewhere between the two.

Participants were also asked to rank the interfaces in order for how much visual attention they felt each one required to use. 17 of 18 participants ranked the interfaces in the following order: GUI (most visual attention), low-res, high-resolution (least visual attention). The remaining participant considered the low-resolution design as

the interface requiring the most visual attention.

After analyzing the video data, we observed that participants had several ways of interacting with the slider widget on the low-resolution prototype. We identified three interaction styles: pushing, sliding and gripping. 60 % of participants pushed the sensels using one, two or three fingers, 20 % slid their fingers above the sensels to interact with them, and just one participant tried to grip each sensel to operate it. None of the participants changed their interaction style during the trials. Participants tended to change the finger with which they interacted with the sensels during the trials – some used just one finger (thumb, index, middle or ring), others used two or three fingers at the same time, and others participants mixed the the number of fingers used to control the sensels for each interaction style. This gives a first insight into how users might interact with sensels, and into how the low-resolution prototype could be redesigned to better facilitate the slider interaction. For instance, bigger sensels could imply using three fingers, whereas small ones could imply using only one finger.

Another relevant observation is that even though all participants were instructed to keep the pursuit error as little as possible at all times, two different behaviours were clear. Some users were clearly ‘chasing’ the blue target area when it jumped instantly from one side of the control to the other; whereas other participants simply waited for the blue target to come closer to their white cursor before they began following it with the physical controls. How this differing behaviour affected the accuracy of each participant is not clear. Controlling or correcting this subjective accuracy requirement *a posteriori* is not straightforward and needs further research. As a comparison, controlling or correcting the subjective speed-accuracy tradeoff for Fitts’ law pointing tasks is a research area in itself [189].

These results support our findings from analysing the video footage, confirming that the touchscreen approach requires the most visual attention while the high-resolution approach requires the least.

C.4 Discussion

We have presented the concept of *Emergeables* (first introduced in [136]³), which combines the flexible, mobile versatility of touchscreen displays with the affordability and precision of tangible controls. The concept aims at facilitating eyes-free interaction with continuous controls on mobile devices.

The results of our experiment show that when switching between several eyes-free, continuous tasks, the high-resolution emergeable prototype is the most accurate. Overall, this prototype is found to be almost twice as accurate as the GUI prototype, and even higher when controlling two parameters at the same time. This result demonstrates the strong potential of high-resolution emergeable controls, showing their improvement over traditional GUI displays – the current interaction style of state-of-the-art mobile devices as described for the case of sliders in Section 2.3 (page 27).

Our next step, then, is to focus on the accuracy of the low-resolution emergeable prototype. In the case of a single slider, the high-resolution prototype provides the best accuracy, followed by the GUI prototype. Although the low-resolution slider provided a lower accuracy over the GUI, a study from Pearson *et al.* [127] shows that a refined version of the low-resolution slider (i.e. 9 sensel rods with micro joysticks instead of navigation switches) provides the same accuracy difference with a GUI slider. This suggests that other aspects of emergeables, like shape transition or the way how the slider is manipulated, might have an impact on performance.

In the case of a single dial, the low-resolution prototype provides almost the same level of accuracy as the high-resolution prototype. This result was expected since dials on both resolutions were operated in the same way, i.e., using the thumb and index fingers to rotate the dial. On the contrary, the GUI prototype is almost twice as inaccurate in comparison with the low-resolution and high-resolution prototypes. This supports the advantage of tangible controls over graphical ones for eyes-free interaction as described in Section 3.1.3 (page 54).

For both single and dual dial tasks, the low-resolution prototype provides almost

³the author of this thesis was part of the research team

the same level of accuracy as the high-resolution prototype. In the case of two sliders, as with a single slider, the low-resolution prototype did not offer a good accuracy level. This makes the need for future improvements in emergeable technology (e.g., in the size of the movable sensels) even more important for complex tasks. In the case of a slider and dial simultaneously, the accuracy provided by the low-resolution dial was able to compensate for the loss in accuracy of the low-resolution slider.

Beyond performance, the user's safety can be at risk in situations where visual attention is critical – e.g., controlling a car stereo while driving (see Section 2.1.2.2, page 15). The results of our video analysis show that emergeables devices require significantly less visual attention than the GUI-based mobile device. Since the pursuit tasks in the study required as much of the users' attention as possible, we can deduce that the best interface for such a task 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 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. Overall, emergeables are a promising direction for mobile user safety, and indeed, other scenarios where eyes-free interaction would be beneficial (as the ones described in Section 2.4, page 33).

In terms of specific widgets, there is no significant difference in the visual attention demanded by high-resolution sliders and dials. Regarding the low-resolution prototype, we anticipated that its sliders would be harder to use than its dials as not only are they an entirely new way of interacting which participants would not be used to, but are also an early prototype design with interaction limitations. Our prediction is that as users accrue increased exposure to the type of interaction, this gap in loss of control between the high- and low- resolution approaches will reduce.

When controlling two widgets at the same time, it requires more visual attention to control one of each type of high-resolution widget (i.e. one slider and one dial) than two of the same (i.e. 2 sliders or 2 dials). We argue that this is due to the different actions required to operate the widgets (i.e. sliding and rotating) which might be

cognitively demanding.

Regarding the subjective preference, users preferred using the emergeables rather than the touchscreen GUI prototype. From the pre-study questionnaire, results show that 73% of participants preferred tangibles over touchscreens, especially for dials (88%). After participation in the study, 100% of participants found the high-resolution prototype easier to use than the GUI prototype, and 72% found the low-resolution prototype easier to use than the GUI prototype. They also rated the touchscreen approach significantly lower on average than both the emergeable prototypes (3.4/10 for the GUI, versus 4.8/10 and 8.8/10 for low-resolution and high-resolution prototypes).

C.5 Conclusion

The goal of *Emergeables* (first introduced in [136]⁴) is to facilitate interaction with continuous controls on mobile devices for situations where eyes-free interaction is required, e.g., using sliders to operate distant appliances (see Section 2.4, page 33). For this, two prototypes were built to test the viability of tangible, continuous controls that ‘morph-out’ of a flat screen.

Our first prototype – a high-resolution shape-changing mobile tangible user interface – 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, at the cost of placing the widgets in four specific locations on the display.

Our second prototype – a lower-resolution sensel-based tangible approach – is an initial implementation providing dials and sliders that can be placed anywhere on its display. We envision that this approach could be refined in future work to become smaller and of higher-resolution.

The findings presented in this chapter allow us to answer the questions posed at the beginning of this appendix (page 73):

- The tested prototypes of the emergeables concept (a high-resolution prototype

⁴the author of this thesis was part of the research team

composed of commercial tangible controls, and a low-resolution composed of sensel-based widget models) proved to have a lower impact on performance and on the required visual attention than a graphical prototype. A high-resolution prototype proved to provide better accuracy (3.5% less error) than the graphical version when manipulating a single widget at a time. Moreover, the high-resolution prototype requires around 74% less visual attention than the GUI version when manipulating a single widget at a time.

- All the evidence suggests that emergeables are easier to use, require less visual attention, are largely preferred by users, and are more accurate to operate than graphical user interfaces. Results strongly suggest that the high-resolution emergeable is the optimum prototype for controlling continuous parameters. This is an encouraging result which justifies the continuation of this ambitious but worthwhile body of work. In addition to this, we have also identified the sensel-based approach as a promising candidate for further development. With additional work, this prototype can be miniaturised and increased in resolution, thus improving the usability and accuracy of its controls.

The obtained results show the potential and benefits of emergeable, high-resolution, tangible controls in terms of accuracy, visual attention and user preference. This is important since continuous controls, such as sliders, are widely used on mobile devices (see Section 2.3, page 27). Furthermore, eyes-free interaction is a desired feature when interacting with mobile devices (see Section 2.1, page 10).

The *Emergeables* concept opens new research avenues, such as one-handed interaction with shape-changing continuous widgets on mobile devices, that we address in Part II Solution Space (page 80).

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