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Bachelorarbeit

Exploring the suitability of shape-changing tangible interfaces to communicate uncertainty

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Abstract

Uncertainty is intrinsic to human nature, and in many real world scenarios it is unavoidable. On a daily basis, humans interact with a multitude of different devices, and the importance of uncertainty in data increases steadily. To name just a few, uncertainty can be found in machine learning or weather forecasts, but also in user inputs like calorie intake. While previous work has shown that people prefer the communication of uncertainty on output, it is still unclear if the same holds true for user input. Furthermore, the means of uncertain input communication is a field that has scarcely been explored yet. Nevertheless, to produce valid outputs containing uncertainty, the input uncertainty has to be quantified first.
In this thesis we propose nine shape-changing tangible interfaces that support uncertain input. Based on the results of a preliminary study in form of a focus group, we have determined the most promising design and present an implementation of a shape-changing slider. In order to evaluate this design, we conducted an explorative user study. Results of the study show that users prefer to have the possibility of uncertain input. In addition, the prototype was rated to be very suitable for uncertain input with an average rating of 6.83 on a 7 point Likert scale. On a higher level, this provides evidence that shape-changing tangible interfaces fit the task of communicating uncertainty. Overall, the predominantly positive user feedback shows promise in uncertain input communication and encourages future exploration.

Kurzfassung

Unsicherheit liegt in der Natur des Menschen und ist in vielen realen Szenarien unvermeidbar. Täglich interagieren Menschen mit einer Vielfalt von Geräten und Daten-Unsicherheit spielt dabei eine immer wichtigere Rolle. Diese Unsicherheit kann unter anderem im Maschinenlernen oder in Wettervorhersagen gefunden werden, aber auch in Nutzereingaben wie der Kalorienzufuhr. Obwohl bisherige Forschung für Ausgaben gezeigt hat, dass Menschen die Kommunikation von Unsicherheit bevorzugen, ist noch unklar, ob selbiges auch für Eingaben zutrifft. Ferner sind die Möglichkeiten für solche Eingaben mit Unsicherheit kaum erforscht. Um jedoch valide Ausgaben mit Unsicherheit produzieren zu können, muss zunächst die Eingabe-Unsicherheit quantifiziert werden.
In dieser Arbeit schlagen wir neun formändernde, greifbare Nutzerschnittstellen vor, die Eingaben mit Unsicherheit unterstützen. Basierend auf den Ergebnissen einer Vorstudie haben wir das vielversprechendste Design ermittelt und präsentieren die Implementierung eines formändernden Sliders. Wir führten eine explorative Nutzerstudie durch, um dieses Design zu evaluieren. Die Ergebnisse zeigen, dass Nutzer die Möglichkeit für Eingaben mit Unsicherheit bevorzugen. Zudem wurde der Prototyp als geignet für Eingaben mit Unsicherheit befunden mit einer Wertung von 6,83 auf einer 7-punktigen Likert-Skala. Auf einer höheren Abstraktionsebene weist dies nach, dass formändernde, greifbare Schnittstellen für diese Aufgabe geeignet sind. Im Allgemeinen zeigt die vorwiegend positive Nutzerresonanz, dass die Kommunikation von Eingabe-Unsicherheit vielversprechend ist, und motiviert weitere Erforschung.

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1 Introduction

Data uncertainty is not just a mathematical concept, but a phenomenon everyone deals with on a daily basis. With today's rich assortment of electronic devices, each person requests and produces increasingly more data from day to day. Since uncertainty is unavoidable in many scenarios like weather forecasts or schedules of public transport, it should be communicated to the users, as it is an important aspect of the data. However, uncertainty is rarely communicated other than in scientific contexts [BD09], even though a sizeable amount of research on uncertainty visualization exists, like adding glyphs [WPL96], modifying geometry [Wit95], or modifying attributes [PA95], among others. This is even more surprising when considering the finding that people do indeed prefer weather forecasts expressing uncertainty over deterministic forecasts [MDL08].

So why is uncertainty so rarely communicated? Among other problems, like the multiplication of data volumes [GS+06] or the confusion caused by its depiction [LSR01; WBR+86], there is a lack of sufficient uncertainty data quality [BD09]. In order to produce valid outputs containing uncertainty, means of data acquisition are required that include this uncertainty. This means that when a user is the source of uncertainty or the mediator of uncertain data, input mechanisms that support uncertain input are required. However, this is a research field that has scarcely been explored yet. So the question arises: *Which input mechanisms are suitable for the communication of uncertain input?* Based on the fact that users preferred uncertainty information on output, it is yet to be clarified if this preference is transferable to input: *Do users prefer to be able to input uncertainty?*

In this thesis, we delve into the realm of shape-changing tangible interfaces to investigate these questions. Among other benefits, tangible interfaces provide multiple interactions at the same time [SH10], rendering them a promising input mechanism for uncertain input, as data containing uncertainty is multidimensional.

To lay the groundworks, we start off by presenting related work on uncertainty, tangibility, and shape-change. In order to get an understanding of how shape-changing tangible interfaces can be used for uncertain input, we provide a glimpse into previous work exploring uncertain input, as well as research on input via shape-change.
To give examples of the problem at hand, we present application scenarios where uncertainty is found within the user input. Following this, we propose a total of nine shape-changing tangible interfaces, that support uncertain input.
As our research is user-centric, we conducted a preliminary study in form of focus groups, to give us an understanding on user needs. These helped us narrow down our five presented

low-fidelity prototypes to the most promising one, the Split Slider.
We built the Split Slider prototype based on our proposed design and the user feedback of the prestudy. In this thesis, we provide implementation details on the hard- and software we utilized for the prototype.
Finally, we conducted an explorative user study to evaluate our prototype and answer the research question of its suitability for uncertain input. Among other results, the study showed that users do indeed prefer having the possibility of uncertain input, and that our prototype is suitable for inputs with uncertainty (and therefore, on a higher level, shape-changing tangible interfaces as well), providing a positive answer to our research question.

Our work encourages future research on the topic of uncertain input communication, and we propose future directives on the important aspects that we have encountered within the scope of this thesis.

Outline

The thesis is composed of the following chapters:

Chapter 2 – Related Work on the topics of uncertainty, tangibility, and shape-change is presented in this chapter.

Chapter 3 – Design Exploration: In this chapter we present application scenarios and propose designs for uncertain input.

Chapter 4 – Prestudy on User Needs: In this chapter we describe the setup and process of our prestudy, and present and discuss the results.

Chapter 5 – Implementation: Here we provide details on the utilized hard- and software of our fabricated prototype.

Chapter 6 – Study: In this chapter we describe the setup, process, and goal of our user study. The results and their analysis can be found in this chapter.

Chapter 7 – Conclusion and Future Work: The final chapter recaps the most important aspects of this thesis and provides future directives.

2 Related Work

In this chapter we explain the terms uncertainty, tangibility, and shape-change as they are found in literature. They lay the groundwork for our research. Afterwards, we present subsequent literature, addressing the communication of uncertainty and communication using shape-changing interfaces.

2.1 Foundations

In this section we present the foundations of uncertainty, tangibility, and shape-change as they can be found in literature.

2.1.1 Uncertainty

> "Information uncertainty is a complex concept with many interpretations across knowledge domains and application contexts."
>
> -MacEachren et al. [MRH+05]

In the following sections we take a closer look at some of these interpretations of uncertainty from different domains, which can be found throughout the literature.

In their research on uncertainty visualization, Pang, Wittenbrink, and Lodha [PWL97] describe uncertainty to include statistical variations or spread, errors and differences, minimum-maximum range values, noise, or missing data. They name three main sources that introduce uncertainty. In data acquisition, uncertainty is inevitable due to inexact measurements. Following that, transformation of the data is another possible source to introduce uncertainty, since the original data is altered through some algorithm or person, which always entails the possibility of incorrectness or imprecision. Finally, visualization itself may introduce uncertainty as well. They state, to give just one example, that radiosity algorithms use approximations in their calculations.

While many see imperfect information within the scope of uncertainty, Gershon [Ger98] sees uncertainty just as one part of imperfect information, alongside corrupt data and information, incomplete data and information, inconsistency, difficulty in understanding and imperfect presentation.

In the field of intelligence analysis, Thomson et al. [THM+05] present the following typology (word-for-word), which describes aspects of uncertainty related to intelligence analysis:

- **Accuracy/error:** difference between observation and reality
- **Precision:** exactness of measurement
- **Completeness:** extend to which info is comprehensive
- **Consistency:** extend to which info components agree
- **Lineage:** conduit through which info passed
- **Currency/timing:** temporal gaps between occurrence, info collection & use
- **Credibility:** reliability of info source
- **Subjectivity:** amount of interpretation or judgment included
- **Interrelatedness:** source independence from other information

In order to get a more general understanding of uncertainty, efforts were made by Skeels et al. [SLSR10]. They reviewed existing literature from different domains and conducted interviews with people working within domains that include uncertainty. Thus they created a classification that represents commonalities in uncertainty across domains. They came up with a layer, dividing different kinds of uncertainty into three levels.

- **Level 1:** measurement precision (variation, imperfect measurements, theoretical precision limits)
- **Level 2:** completeness (missing values, sampling, aggregation)
- **Level 3:** inferences (predictions, modeling, describing past events)

Furthermore they describe disagreement and credibility, which span all three levels. At this juncture, disagreement means for example different measure results of the same measurement, overlapping but not identical datasets, or different conclusions being drawn from the same data. Credibility derives from the source of the data.

In their research on uncertainty visualization, Boukhelifa and Duke [BD09] take a critical look at visualization practices. The important aspect of uncertainty in visualization is rarely seen “other than as a laboratory exercise”, according to their analysis. They suggest that in order to make uncertainty visualization successful, improvements need to be made for capturing and modeling of uncertain data. They propose that an agreement on data and its implementation is required, as well as a socially agreed system for depiction. While it is very often attempted to eliminate uncertainty altogether, they propose that instead there should be ways to gather it, since humans mediate the provision of data and thus always introduce a degree of uncertainty through subjectivity, non-specificity and the imperfectness of the human memory. This motivates our research in looking for input mechanisms that allow users to include uncertainty information when applicable.

Within the domain of weather forecasting, Morss, Demuth, and Lazo [MDL08] analyzed the public's perspective on everyday forecast uncertainty via a U.S. wide survey. Among several of their results, we are mostly interested in the following two findings. First, their results showed that most people inferred uncertainty when given a deterministic temperature forecast. And second, a significant majority of the respondents preferred weather forecasts expressing uncertainty to deterministic single-valued forecasts. This raises the question whether those discoveries can also be transferred to inputs with uncertainty. In our research we will examine if users prefer to input uncertainty instead of a deterministic value when presented with an application scenario containing uncertainty.

2.1.2 Tangible User Interfaces

In this chapter we take a closer look at tangible user interfaces (TUIs), also known as graspable user interfaces [UI00].

> "A Graspable UI design provides users concurrent access to multiple, specialized input devices which can serve as dedicated physical interface widgets, affording physical manipulation and spatial arrangements." Fitzmaurice [Fit96]

Similar to traditional graphical user interfaces (GUIs), physical devices can be used as controllers for logical functions connected to widgets within the interface. However there is usually only one physical device (a mouse) for a GUI, which is being attached to and detached from different logical functions of the system, while there can be a multitude of tangible input devices at one time, each attached to one or several logical functions. Thus, multiple functions can be accessed simultaneously using TUIs. The use of physical objects as input devices allows for a larger expressive range of gestures and grasping behaviors as well as for the use of our empirical knowledge on manipulating the physical world [Fit96].

In their research on frameworks for tangible user interfaces, Ullmer and Ishii [UI00] propose their "MCRpd" model, adjusting the well-known "Model View Controller" (MVC) model to fit tangible user interfaces. While keeping the "model" and "control" elements, they divide the "view" into physical representations "Rp" and digital representations "Rd". Contrarily to the MVC model, which strictly separates graphical representation and control, their MCRpd model highlights the integration of physical representation and control, since most tangible input devices embody a physical representation of their internal state. They formulate the following four key characteristics (word-for-word):

1. Physical representations are computationally coupled to underlying digital information.
2. Physical representations embody mechanisms for interactive control.
3. Physical representations are perceptually coupled to actively mediated digital representations (graphics and audio).

4. The physical state of interface artifacts partially embodies the digital state of the system (e.g. TUIs are persistent, thus they cannot just be banished from existence like a GUI window).

Following a different philosophy, namely that tangibility is not a binary characteristic but instead a continuous attribute, Fishkin [Fis04] proposes a two-dimensional taxonomy that describes how "tangible" a user interface is. The two dimensions are *embodiment* and *metaphor*. The taxonomy differentiates between four levels of embodiment: Full, Nearby, Environmental, and Distant. As for metaphor, they propose the following levels (word-for-word):

- **None:** [...] No metaphor [is] employed at all.
- **Noun:** An <X> in our system is like an <X> in the real world.
- **Verb:** <X>-ing in our system is like <X>-ing in the real world.
- **Noun and verb:** <X>-ing an <A> in our system is like <X>-ing something <A>-ish in the real world.
- **Full:** To the user the virtual system is the physical system.

2.1.3 Shape-Changing Interfaces

To get a general overview on shape-changing interfaces, Rasmussen et al. [RPPH12] provide a review covering a wide range of design space and open research questions on shape-change. They propose the following types of change: orientation, form, volume, texture, viscosity, and spatiality, which are all topologically equivalent. The last two do not necessarily deform objects (e.g. a change in viscosity can change the tangibility of an object while remaining in the same physical shape). With all these types of shape-change, an object can change from one shape to another through continuous deformation, without dividing or joining elements. Differing from these types, shape-change through adding/subtracting and permeability are the two other shape-change types mentioned, which are not topologically equivalent to the first ones.

Based on the idea of seeing shape-change as deforming a mesh, a shape made of control points, Roudaut et al. [RKLS13] provide another taxonomy of the different types of shape-change, consisting of the following ten features:

- **Area:** surface area of a shape
- **Granularity:** density of physical actuation points
- **Porosity:** ratio of the area of perforated parts to the total area
- **Curvature:** curviness of the surface
- **Amplitude:** range of displacement of control points

- **Zero-crossing:** capability of a shape to have wave-like forms
- **Closure:** how "closed" a shape is
- **Stretchability:** how much the surface distorts between two control points
- **Strength:** force needed to move a control point from minimum amplitude to maximum
- **Speed:** time needed to move a control point from the rest position to the maximum amplitude position

Rasmussen et al. [RPPH12] take a look at interaction with shape-changing interfaces and differentiate between three different types. The first one is no interaction, meaning that shape-changing properties are solely used for output. The second one is indirect interaction, which takes implicit input and provides shape-changing output. Finally, there is direct interaction, which includes shape-changing input as well as shape-changing output. The latter is divided into shape-changing input and output on the same object and input on one with output on a remote object or surface.
Our research falls into the category of direct interaction, as our prototype (see chapter 5) was used for input and the prototype being a slider always provides visual output through the position of its thumbs. We did however include additional graphical output.

Also on the topic of interaction, Coelho and Zigelbaum [CZ11] give a different insight. According to them, shape-change can be described as physical transformations, which can be *perceived* and *acted upon* by a user. They list four distinct ways shape-change can be perceived, being (1) the overall shape changes, (2) the external surface quality changes, (3) homeomorphic changes, and (4) any combination of said changes. On the other hand, shape-changing shapes can respond to a deformation exerted by a user, thus providing the following interactions (word-for-word):

- Objects can gain a new physical shape, and the transformation mapping between input and output can be amplified, dampened, modulated, or simply remain the same.
- Objects can respond with force-feedback and counteract the user's deformation.
- Objects can not respond at all, recording the user's action and applying it in some other place or context.
- Objects can constrain and limit the deformation imposed by the user.

As for the purpose of shape-change, Rasmussen et al. [RPPH12] mention hedonic aims (which include aesthetics, emotion and stimulation), explorative aims, providing toolkits, and functional aims (which are communication of information, dynamic affordances, haptic feedback, and construction).
Our research falls into the categories of explorative aims, haptic feedback and most notably communication of information.

2.2 Communication Mechanisms

In this section we present related work that delved into the communication of uncertain input, as well as work exploring how shape-changing interfaces can be leveraged as input mechanisms.

2.2.1 Uncertain Input

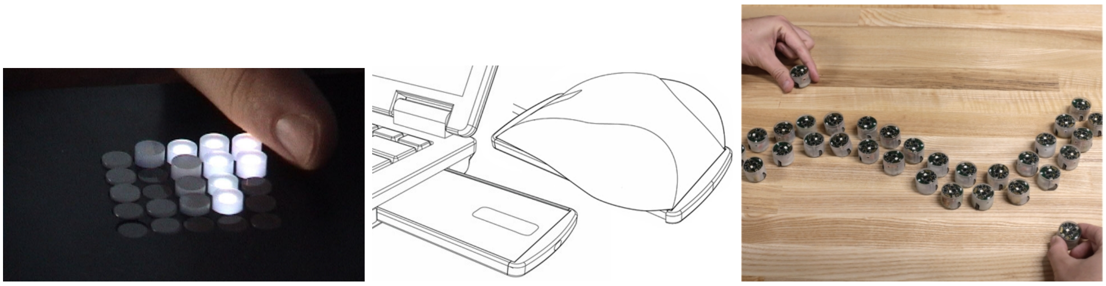
Providing users with the possibility to give input about their uncertainty, accompanying their actual data input, is a field that is not very well explored yet.

In their research on input controls for uncertain data, Greis et al. [GSK+16] used probability distribution sliders within the GUI with varying degrees of freedom as their input method. The study showed that users with very limited statistical knowledge performed best using the flexible range slider (two degrees of freedom), while users with more statistical knowledge performed better with sliders that had three or more degrees of freedom.

On the other hand, input technologies like touch, recognition based input and next-generation interactions produce input with differing degrees of uncertainty, although these input technologies were not designed for the purpose of giving input on uncertainty, but instead entail it as a byproduct of imprecise inputs. In order to handle these kinds of inputs, Schwarz et al. [SHMW10] presented their framework for input with uncertainty. However, in our research inputs containing uncertainty are purposefully and explicitly made, so we can treat these inputs as regular inputs.

2.2.2 Input with Shape-Changing Interfaces

Closely related to our research at hand, Coutrix and Masclet [CM15] explored the opportunities and limits of a resizable tangible slider. Tangible sliders do not need visual attention and thus are successfully used in practice. Since they are real-world physical objects, a trade-off has to be made between the physical size of the slider and the respective precision. Their research provided users with a possibility to balance between those two concerns on the fly, by allowing them to modify the size of the slider. Their results showed that this design provides a promising combination of space efficiency and pointing performance, if the time interval for size changes is not too small (approx. 9s).
With the following few adjustments, their design could also be used as an input method for information including uncertainty. By interpreting the size of the slider as the uncertainty (smaller size means less precision and thus more uncertainty), this slider would be able to represent a Gaussian distribution (uncertainty ~ variance; value ~ mean). With two degrees of freedom, it would be very similar to the flexible range slider described by Greis et al. [GSK+16].



(a) Lumen [PNM+04] **(b)** Inflatable Mouse [KKL+08] **(c)** Zooids [LKP+16]

Figure 2.1: Shape-Changing Input Examples – Left: Input by pushing light-guides down; Middle: Input through squeezing; Right: Input through movement.

On the topic of communication with shape-changing interfaces, Poupyrev et al. [PNM+04] present their interactive display "Lumen" (Figure 2.1a shows interaction with Lumen). It consists of a two-dimensional array of light guides, which can be changed in height and color in order to represent shapes, images and physical motions. These motions are controlled by shape memory alloys within the light guides, which can be heated or cooled down. It also provides interaction with a built-in SmartSkin sensor [Rek02] on the light guides surface, recognizing user hand shapes and finger motions through touch.

In their research Kim et al. [KKL+08] propose their idea of an inflatable mouse (see Figure 2.1b). In addition to the high portability when the mouse is deflated, new affordances arise from the deformation possibilities. The system as well as the user can cause a pressure change. Pressure changes executed by the system resulting from deformations of the mouse provide haptic feedback to the users, but at the same time pressure changes made by the user can be leveraged as an input signal. They propose several new input methods, which combine squeezing the sides of the mouse or pressing the top part of the mouse, while using the conventional mouse-inputs such as mouse buttons, mouse wheel, and mouse movements is still possible and can even be done simultaneously with the new interactions. These input methods are closely related to our research, as we are investigating two multidimensional inputs as well (value and uncertainty).

Taking a different approach towards shape-changing by using multiple small units to give the illusion of a coherent shape, Le Goc et al. [LKP+16] propose their zooids design (see Figure 2.1c). They define it as a swarm user interface, an interface comprised of small autonomous robots, that handle both display and interaction. Being able to control all robots at the same time but still having control over the movement of each robot autonomously, allows the usage of these robots as physical pixels. Thus it allows visual output, with the help of LEDs on each robot, that is not limited by a pixel grid. However, the visual output is limited by size and amount of the robots. In addition to the output, any manual displacements of the robots is registered, and thus every single robot can be used as a two dimensional locational input device with absolute positioning as well as positional change.

3 Design Exploration

In this chapter we present four possible application scenarios where uncertainty is often encountered. Afterwards we propose nine different low-fidelity prototype designs which support inputs with uncertainty. The presented prototypes include slider-based, dial-based, and other more explorative designs.

3.1 Application Scenarios

In this section we present four application scenarios, where user input might entail uncertainty, in order to show the relevance of this research, and also to have a basis for our different design approaches. Additional application scenarios were found within the prestudy (see chapter 4) and will be presented in the results section. In the following, we present the application scenarios of calorie intake, ecological footprint, search, and shopping.

3.1.1 Calorie Intake

Nowadays many people are very aware of their physical shape, and in addition to doing sports they also adjust their eating habits. There are many (mobile) applications, e.g. MyFitnessPal[1] or LoseIt![2], on the market which monitor ones personal calorie intake. A common problem among these applications however is the fact that most if not all of them require exact input values. As everyone knows one does not always have a weighing scale at hand, e.g. when traveling. This lack of knowledge and requirement of an exact value will evoke thoughts like: "I guess that apple weighed 150g". Thus we propose that the possibility to make inputs with uncertainty is an important aspect for calorie intake applications. In this case the most natural thought process is probably "I guess that apple weighed between 150g and 200g.", which represents a two dimensional input similar to the flexible range sliders [GSK+16]. In addition, the calorie density of certain food items might differ: A burger from a fast food chain will most likely feature different calorie values compared to one from a restaurant. Taking calorie density into consideration as well, introduces an additional dimension of uncertainty to the input.

[1]MyFitnessPal, https://www.myfitnesspal.com/
[2]LoseIt!, http://loseit.com/

3.1.2 Ecological Footprint

With the rising threat of climate change, the awareness of ecological footprints is steadily increasing. Again, the market offers a wide variety of applications, e.g. GiveO2[3] or Leafully[4], that provide functionality to monitor personal ecological footprints. While some of these even automatically track travels via GPS, the economical footprint of a person can hardly be captured fully automated. First of all, people might not always have their mobile phone with them, and second, their energy consumption for electricity when not at home cannot be tracked automatically that easily. So again they will find themselves in situations where they have to manually input data on when they used which device for how long and what the corresponding estimated consumption for that time is. So the input for one entry could contain multiple dimensions for time with uncertainty and dimensions for consumption over time with uncertainty.

3.1.3 Search

Another application scenario almost every internet user is familiar with is searching. With the most known representative being Google[5] search, there are still numerous other online search engines, but also lots of systems that allow searching within local databases. Irrespectively of the search engine in use, some degree of uncertainty is likely bound to the search, be it that users do not necessarily always know what they are looking for precisely, or uncertainty on the correct spelling of the search term. While many search engines tolerate incorrect spellings to some degree and propose similar terms that have been searched for, the system has all control over the uncertainty and no control about the input uncertainty is given to the user. Strings however pose a difficult problem, since they do not describe a continuous function and thus would require a different interpretation of uncertainty than the numerical approach we are using. So instead we are more interested in a simplified version, being numerical search. This numerical search can for example be found when searching for dates. Essentially, the input for a numerical search query can contain multiple dimensions for each number including uncertainty.

3.1.4 Shopping

Not too different from the search application scenario, online shopping has some similar features. This includes the fact that users are given the ability to search for specific articles and that they introduce uncertainty to the system, since not all users know exactly what they

[3]GiveO2, www.giveo2.com
[4]Leafully, https://leafully.com
[5]Google, https://www.google.com/

want to buy beforehand. This uncertainty is very hard to grasp however, thus more specific factors that can be used to describe products are more interesting to us. These factors can often be applied as filters on shopping sites and range from clothing sizes over clock speed of a processor to the most common filter, being the price. Again, we limit ourselves to numerical filters only. Each of these filters might entail uncertainty and according input mechanisms might become a necessity.

3.2 Prototype Exploration

In this section we present nine possible designs for shape-changing tangible devices, that allow users to input information with uncertainty. The design approaches are separated into slider-based, dial-based, and other designs. This separation is loosely based on the taxonomy of Card, Mackinlay, and Robertson [CMR91], who differentiate between linear and rotary input, while designs we sorted into the other section are more explorative. The input on uncertainty can be implicit or explicit. Implicit means that the input on entered values contains the uncertainty (e.g. inputting two values as an interval), while explicit input means that the uncertainty input is separated from the value input (e.g. the mean value is entered, and an additional input is made for the degree of uncertainty). We will use the taxonomy of Roudaut et al. [RKLS13] (presented in section 2.1.3) to classify our designs. An overview of our classification can be seen in Table 3.1.

At this point the question arises why using a tangible interface would be preferable to a traditional graphical interface.
In their research on tangible user interfaces, Shaer and Hornecker [SH10] describe the strengths of these interfaces. These include the fact that tangible interfaces provide interactions with the physical world, like moving, squeezing, or stretching, which are familiar interactions to human users. In most cases, the physical state of tangible devices themselves give a visual representation of their state within the system (e.g. the thumb position of a slider is its visual representation and usually correlates to its digital value in a linear fashion). Furthermore, their physical nature can limit affordances. Taking a look at a physical slider, this can easily be understood, as the slider thumbs themselves cannot be moved past the outer limits of the slider body, which is usually also a logical limitation, as sliders represent inputs within intervals.
On top of that, tangible interactions are space multiplexed, meaning that multiple interactions can be performed simultaneously. Suppose two dials are next to each other, users can manipulate them at the same time, using one hand per dial, while doing similar things with a mouse and keyboard poses a difficult task. There are of course other input mechanisms, like multi-touch, that also allow for multiple interactions simultaneously. Another advantage comes with the fact that tangible interfaces can provide tactile feedback. Firstly, this includes that the state of a device can possibly be felt through touch and therefore does not require visual attention. Secondly, interactions can be complemented with additional feedbacks, like pressure or vibrations, in order to give the interaction a metaphorical meaning for the user.

Feature	Slider-Based	Dial-Based	Other
Area		Expandable Dial	
Granularity	Split Slider		
Porosity			Hole Pad
Curvature			Curve
Amplitude		Pressure Dial	
Zero-crossing			Curve
Closure		Pinch Dial	
Stretchability			Stretch Pad
Strength	Spring Slider	Pinch Dial	
Speed	Speed Slider		

Table 3.1: Design Taxonomy – Classification of our design approaches within the taxonomy of Roudaut et al. [RKLS13], also separating between slider-based, dial-based, and other designs.

Horn et al. [HSCJ09] provided evidence that tangible interfaces can be more inviting and are better at encouraging children, particularly girls, to take an active role in exploring. These advantages are especially relevant in a public setting, for example a museum exhibition, where the appeal to use these tangible interfaces plays an important role.

3.2.1 Slider-Based Designs

Sliders allow for value inputs within a given interval (slider bounds) and are a widely spread concept, especially in graphical user interfaces for example with scroll bars. In this section we propose three possible slider designs that support uncertain input, these include the Split Slider, Spring Slider, and Speed Slider.

Split Slider

The basic idea of this slider design is a splittable thumb. Figure 3.1 shows a low fidelity sketch of the design. The slider can be used in one, two, or three thumb mode. This allows users to input deterministic values just like with any other slider by using one thumb mode. When needed however, splitting the thumb allows for multi-dimensional input and thus provides the possibility of making inputs with uncertainty. In the two thumb mode, the slider works like a physical version of the flexible range slider [GSK+16], meaning that users can input interval limits for a probability distribution in between. Respectively, the three thumb mode resembles the flexible range best estimate slider [GSK+16], allowing for more detailed information about the probability distribution by using the middle thumb as the maximum

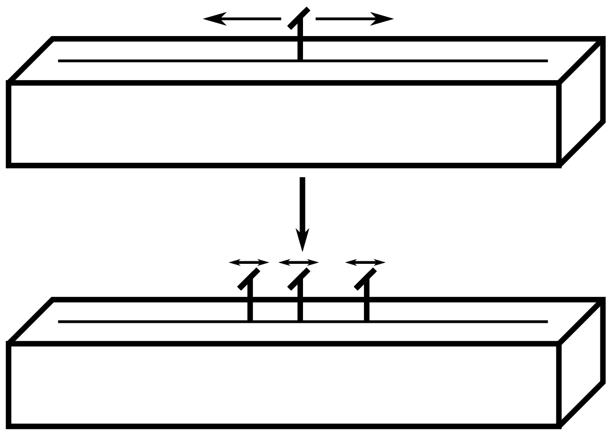


Figure 3.1: Split Slider – The thumb of the split slider can be split into two or three separately movable thumbs. These thumbs are used to communicate the uncertainty of the user.

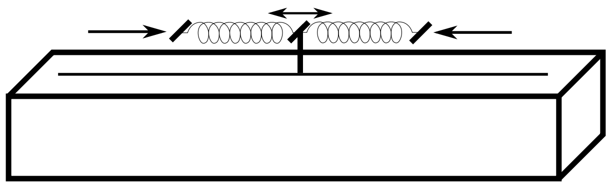


Figure 3.2: Spring Slider – The thumb of the spring slider declares the value of the input while compressing the springs allows for communicating the uncertainty.

value. Within the taxonomy of Roudaut et al. [RKLS13] this design fits into the granularity feature when considering the thumbs as actuation points of the system. The uncertainty input for this slider is implicit.

Spring Slider

The spring slider, which can be seen in Figure 3.2, works like an ordinary physical slider, where the position of the thumb represents the value. Additionally, a mechanism is added to the thumb, that can be pinched together. This mechanism provides input on the degree of uncertainty. The more it is pushed together, the more certain the input. Due to the maximum amplitude of the springs, this design has a natural limit for the range of the probability distribution, which could be tackled by scaling the spring size up to the slider size. The spring slider design belongs to the strength feature of the taxonomy, since force has to be applied to input the amount of uncertainty. If the outer spring positions are used directly as positional input, this design provides implicit input, otherwise it would be explicit.

Speed Slider

While the speed feature of the taxonomy is referring to the speed of the system moving the actuation points, it is also possible to incorporate the speed in which the user moves parts of the device as input. We propose a very simple slider (it could also be any other tangible input device with movable parts), for which we interpret the time needed to select the value as the input speed and furthermore as the level of uncertainty. A value is interpreted as more certain, the faster it is selected. This however introduces an unwanted side effect. Coming along with a fast selection of a value is an inherent lack of precision and thus another, unwanted, source of uncertainty. This could be fixed by having the speed input as a separate input in another direction. Independent of the precise implementation, this design provides explicit uncertainty input.

3.2.2 Dial-Based Designs

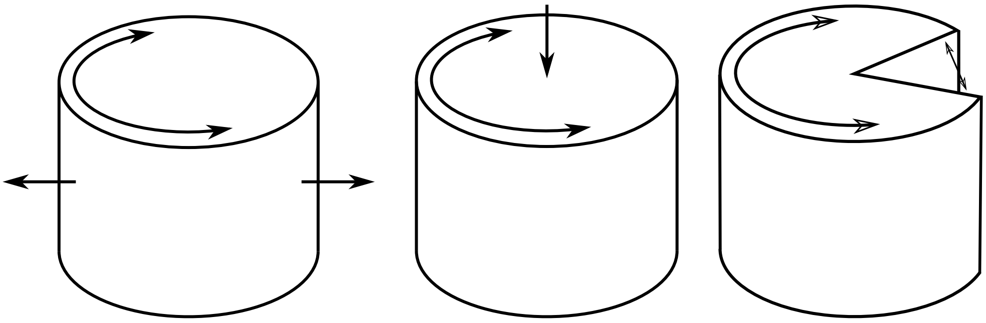
Dials allow rotary value input. The rotation can either be infinite or limited to an interval. Dials are commonly known as they have become the to-go input mechanism for volume control. In this section we present three dial-based input devices for uncertain input: the Expandable Dial, the Pressure Dial, and the Pinch Dial.

Expandable Dial

In addition to the traditional dial interaction, the Expandable Dial can also be increased or reduced in size. This allows for a two dimensional input. Using the rotational input a value can be selected, just as with a traditional dial, while the second dimension, the expansion of the dial, allows for additional uncertainty information. The value can be interpreted as the maximum of a Gaussian distribution, while the expansion represents the variance. The more uncertain users are about their input, the more they can expand the dial. Interaction with the expandable dial can be seen in Figure 3.3a. We categorized this design into the area feature, since the shape-changing portion of the design changes the area seen from the top. The uncertainty input for this dial is explicit.

Pressure Dial

The Pressure Dial also allows for two dimensional input. The first dimension, representing the value, is measured via rotating the dial, while the second one is entered via pressing the dial downwards (see Figure 3.3b for a low fidelity sketch). This second dimension is interpreted as the uncertainty, while the stronger/further it is pushed down, the more certain the input is. This can either be realized by a compressible material or by leaving free space underneath the dial into which it can be pushed into. Either way, inputs in this second dimension modify the



(a) Expandable Dial **(b)** Pressure Dial **(c)** Pinch Dial

Figure 3.3: Dial-based Designs – Common in all three of these designs is the fact that the rotational input represents the value. The input on uncertainty is achieved by (a) expanding , (b) pushing down or (c) closing the respective dial.

(perceived) height of the dial, thus we placed it into the amplitude category of the taxonomy. As with the Expandable Dial, the uncertainty information is entered explicitly.

Pinch Dial

The Pinch Dial (which can be seen in Figure 3.3c) works very similar to the Pressure Dial. It also allows for rotational input for the value, and input for the uncertainty is achieved by pinching the open space of the dial together. The further it is pinched together, the more certain the input. The openness of the hole also gives a visual representation, as it covers a wider range of values when opened. This dial again allows for a two dimensional input for information with uncertainty. Within the taxonomy the Pinch Dial fits into the closure category. Just like the other dial-based designs, uncertainty input is explicit.

3.2.3 Other

The following three designs are very explorative and cannot easily be classified into the taxonomy of Card, Mackinlay, and Robertson [CMR91]. We propose the Stretch Pad, the Hole Pad, and the Curve.

Stretch Pad

The idea of the Stretch Pad is that a two dimensional pad (could also be one or even three dimensional) on which stretchable data points can be placed. This design can be seen in Figure 3.4. The stretch pad would fit the application scenario of the ecological footprint especially well, since a timeline of a day could be modeled on the x-axis and the energy

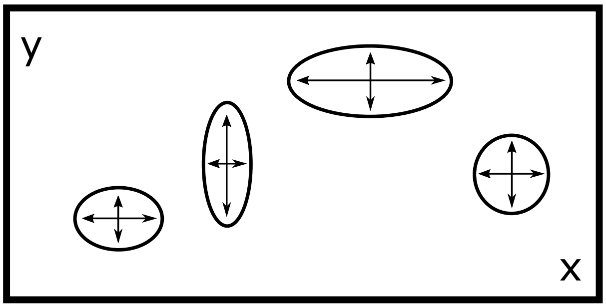


Figure 3.4: Stretch Pad – The Stretch Pad is a two dimensional pad, on which data points can be added and stretched. The location of each data point represents its value while the distortion represents the uncertainty.

consumption on the y-axis. Uncertainty on a data point for either dimension can be expressed by stretching the data point in the respective dimension. As the name suggests, this design fits into the stretchability feature of Roudaut's taxonomy. If the stretched bounds directly represent the interval input, uncertainty input is implicit, otherwise it would be explicit.

Hole Pad

The Hole Pad essentially follows an approach opposite to that of the Stretch Pad. Making use of the porosity property of a two dimensional pad, it allows modeling the absence of data. Similar to the game "Battleship", holes can be input to signify that the probability of the value in this spot equals zero. Alternatively, the depth of holes could be used for a more precise modeling of the probability, while deeper holes represent values with lower probability. Additional clarification is needed on the behavior of values outside of holes. They either can all be equally likely, or the likelihood of each value can be dependent on the distance to nearby holes. Uncertainty input is implicit if no scaling is applied.

Curve

The idea of the Curve is for users to be able to model the probability distribution of the input one to one with a deformable line. This allows for an arbitrarily precise distribution of uncertainty for one dimension, but could also be extended into a two dimensional surface. While this approach allows the most precise input on any uncertainty, at the same time it requires the most statistical knowledge in order to do so. Especially for the two dimensional surface shaping, the precise modeling of the distribution might prove a difficult task since possible states are almost endless. Within our taxonomy this model fits the curvature and zero-crossing feature. Uncertainty input is explicit, as uncertainty is the actual input, while values are coordinates where input is made.

4 Prestudy on User Needs

In order to help us better understand user needs for uncertain input, we conducted a preliminary study in form of a focus group tackling the issue. In this chapter we present the study setup and process. This is followed by the presentation of our preliminary prototypes. In the end, we reveal the results of the study and discuss them.

4.1 Method

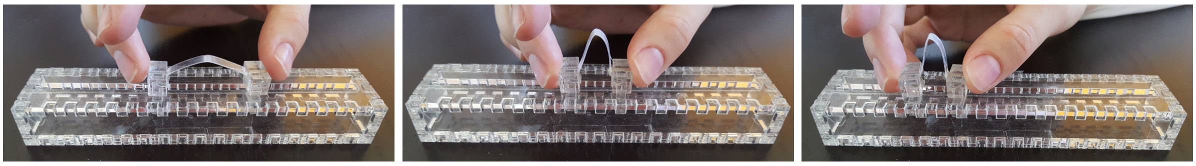
Since we wanted to obtain a general opinion on input of uncertain data and also a discussion when evaluating the prototypes, we decided for focus groups as our study design. The two conducted focus group sessions had an overall length of approximately 60 minutes, with six persons participating in each group. During the sessions, photographs were taken and audio was recorded, to ensure the completeness of our gathered data.

4.2 Apparatus

For the focus groups, five prototypes were built based on our design exploration (see section 3.2), which had low fidelity. In the following we present these prototypes in more detail.

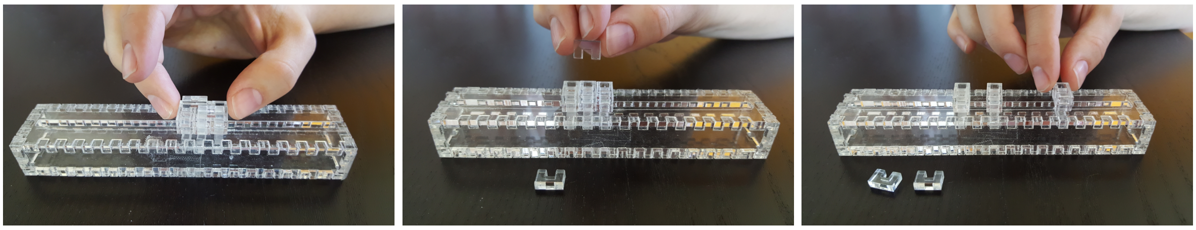
4.2.1 Spring Slider

We used 4mm thick, transparent plastic as material for the slider. With the help of a laser cutter, we cut six sides of a cuboid and glued them together in order to get the slider body with measures of 150mm x 30mm x 20mm. We cut a long but thin hole into the top side, into which the slider thumbs were placed. The prototype, including the thumbs, and the user interaction can be seen in Figure 4.1. The thumbs themselves were also made from plastic and were t-shaped at the bottom for stabilization and cuboid on top for user interaction. We used two thumbs connected by a bent piece of plastic, functioning as a spring.



(a) Basic Position **(b)** Squeezed **(c)** Move

Figure 4.1: Spring Slider – From the basic position (a) certainty input can be made through squeezing (b). The value input works like a normal slider through moving (c).



(a) One Thumb Mode **(b)** Splitting Interaction **(c)** Three Thumb Mode

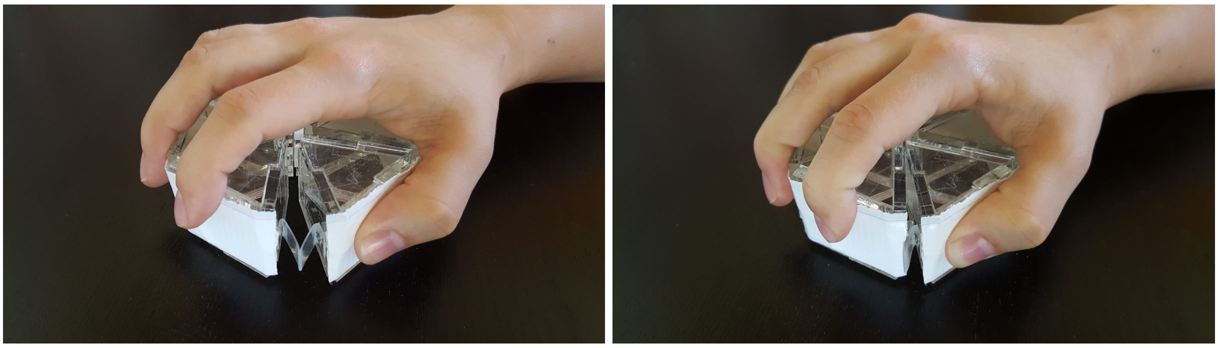
Figure 4.2: Split Slider – From the one thumb mode (a) bridges can be removed (b) to increase the amounts of thumbs. Up to three thumbs (c) can be used for inputs including uncertainty.

4.2.2 Split Slider

For the Split Slider we used the same material and same box shape as for the Spring Slider. However, instead of two, it had three thumbs. Those thumbs had holes cut into the topside and could be connected using a small plastic bridge. Removing these bridges represented the splitting interaction. It can be seen in Figure 4.2, alongside the one thumb and three thumb input modes.

4.2.3 Pinch Dial

The Pinch Dial was also made from the same plastic as the sliders described above. We created six equilateral prisms and connected them into a hexagon, roughly resembling the round shape of a dial. They were held together on the outside with adhesive tape, which was cut open in one spot between two prisms, where a bent piece of plastic was screwed in between, again functioning as a spring. Figure 4.3 shows this open spot with the spring and the pinching interaction of this dial design.



(a) Open **(b)** Pinched

Figure 4.3: Pinch Dial – Values are selected through rotational input. Without force, the dial is in an open state (a) and through pinching (b) certainty can be expressed.

Figure 4.4: Pressure Dial – Rotational input is used for value selection. Pressing it downwards represents the amount of certainty of the input.

4.2.4 Pressure Dial

For the Pressure Dial we used an industrially manufactured "PowerMate Bluetooth"[1]. The aluminum dial allowed for infinite rotational input and had a binary pressure detection to represent our imagined pressure interaction, which should however be an analog one if built for an actual prototype. The dial can be seen in Figure 4.4.

4.2.5 Expandable Dial

For the Expandable Dial we had two prototypes at hand from previous work. One was made from paper and could be reduced in size by squeezing the sides, while the other one was made from plastic and had 12 small concave disks for better finger grip, that could be used to rotate the dial and at the same time change the size of the prototype. Figure 4.5 shows interaction with the plastic design.

[1]https://griffintechnology.com/intl/powermate-bluetooth

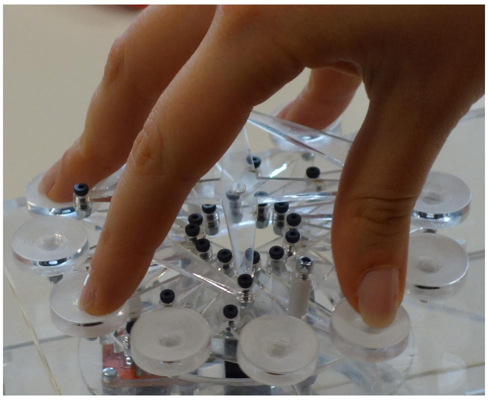


Figure 4.5: Expandable Dial – Value inputs can be made through rotating the dial, while uncertainty input is expressed through expanding and compressing the dial.

4.3 Task and Procedure

During the focus group sessions, the participants were given post-its to note down any ideas they came up with and later received the five preliminary prototypes (see section 4.2) in order to examine them and give feedback.
They were asked to do the following tasks (in the given order):

- **Consent Form:** Participants had to sign the consent form, most notably including the right to drop out, guarantee of anonymity and acceptance of audio/photo recording.
- **Demographic Information:** Each participant filled in a sheet with demographic information. We were interested in their gender, age, highest educational degree, profession and field of study/work.
- **Introduction:** The participants of the focus group introduced themselves, stating their name, field of study/work, and where they experienced uncertainty before (beginning with the conductor, to give an example for uncertainty).
- **Scenarios:** Each participant was given post-its to write down one answer per post-it for the following question: "Which scenarios can you think of where you were or could be uncertain about an input?"
- **Ranking:** Each participant was handed a red and a green post-it, red symbolizing a higher priority. The scenarios from before were presented on a board, and everyone had to rate the two scenarios that seemed most important to them (Figure 4.6 shows the idea board of the second focus group).
- **Group Designs:** The participants were split into groups of two. Each group was assigned one scenario (the highest rated ones from the previous task) and had to think of ideas that could help users to make inputs with uncertainty for their respective scenario. Afterwards, each group briefly explained their idea to the focus group.

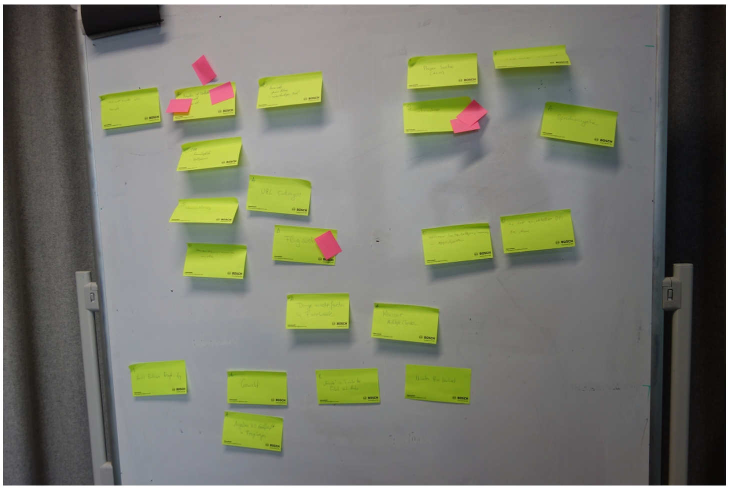


Figure 4.6: Idea Board - Green post-its contain one uncertain input scenario per post-it. Pink post-its represent importance ranking for the respective scenario. Note: We did not use green post-its for second priority, since three different scenarios had been chosen already.

- **Evaluation of our Designs:** We briefly introduced our designs. Each group was then assigned one of the prototypes and had to think about advantages/disadvantages, improvements or suitability of their respective prototype for the different scenarios. Again, each group presented their findings.
- **Statistical Knowledge Test:** For the last task each participant filled in a two question version of the Berlin Numeracy Test [CGS+12], to give us a rough idea of their statistical knowledge. In order not to discourage the participants before the work in the focus group, we decided to place this task at the very end. The detailed questions can be found in appendix in section A.1.

Finally, we collected all materials produced during the focus group session. In order to identify the contribution of each participant while not endangering their anonymity, we had assigned a unique character to each participant at the beginning of the session, which had to be written on every sheet of paper.

4.4 Participants

The study consisted of two focus groups with six participants each. They were recruited via personal invitations. All participants were (former) students and ranged between age 20 and 34 ($M = 24.92, SD = 3.65$). Two of the participants were female. The precise demographic participant data is depicted in Table 4.1 and Table 4.2. We also did a two-question version of the Berlin Numeracy Test [CGS+12] (see Table 4.3a and Table 4.3b for details) to get a rough

Participant	Gender	Age	Highest Degree	Job	Study Course
A	f	26	1. State Examination	Trainee Teacher	English, Sports
B	m	34	B.Sc.	Student	Psychology
C	f	25	B.Sc.	Student	Software Engineering
D	m	23	A level	Student	Software Engineering
E	m	20	A level	Student	Chemistry
F	m	26	B.Sc.	Student	Mathematics

Table 4.1: Focus Group 1 - Demographic data of the participants.

Participant	Gender	Age	Highest Degree	Job	Study Course
A	m	27	Diploma	Academic Staff	Informatics
B	m	23	A level	Student	Media Informatics
C	m	21	A level	Student	Media Informatics
D	m	26	A level	Student	Media Informatics
E	m	22	A level	Student	Media Informatics
F	m	26	M.Sc.	Academic Staff	Human-Computer-Interaction

Table 4.2: Focus Group 2 - Demographic data of the participants.

estimate on the participants' statistical knowledge. The participants scored an average of 1.5 out of 2 correct answers ($SD = 0.67$). So overall, they were on the higher end of the scale in terms of statistical knowledge.

Participant	Question 1	Question 2
A	✓	✓
B	✓	✓
C	✓	✓
D	✓	x
E	✓	x
F	✓	✓

(a) Focus Group 1

Participant	Question 1	Question 2
A	x	x
B	✓	✓
C	✓	✓
D	✓	✓
E	x	✓
F	x	✓

(b) Focus Group 2

Table 4.3: Berlin Numeracy Test Results - Overall focus group 1 achieved more correct results. However they seemed to struggle more with Question 2, which was supposedly more difficult, while the second group mostly struggled with Question 1.

4.5 Results

In this section we present the results of the focus group for each individual task, keeping the order in which the tasks were given to the participants.

4.5.1 Scenarios with Uncertain Input

We present the input scenarios our participants came up with, and propose groupings where possible.

Uncertain memories/lack of knowledge: Many scenarios can be traced back to missing or imprecise memories or knowledge that has never been learned in the first place.
This includes rarely used personal data, for which the participants mentioned the *social security number* or miscellaneous *customer numbers.* Another group of scenarios are passwords, namely *passwords for different accounts* (every account might have a variation of a standard password, or entirely different passwords) and entering *passwords into the console*, which also introduces uncertainty with the lack of visual feedback.
Finally, they mentioned *url endings* and inputs on *body size and weight.*

Unclear instructions/missing competence: In this scenario, we included complicated forms like the ones for *tax return*, *BafÖG* (federal training assistance act in Germany), *patient forms* demanded by doctors, or the personal *medical record.* All these forms require rather uncommon knowledge.

Search: Furthermore, the participants mentioned several search application scenarios. While the first one mentioned was a rather unspecific *"general uncertainty when searching"*, more specific formulations like *"paper search"* on e.g. Google Scholar[2] and *"finding things that you had once found before"* were also among the scenarios.

Unfamiliar input mechanisms: Another category was the unfamiliarity with input mechanisms. Specifically when using *new input devices*, for example a new mouse with possibly different DPI settings or a different button layout, users experience uncertainty as they might behave differently from their previous input devices. *Key bindings* also introduce uncertainty, as they are not globally defined, and thus can behave differently for every operating system or application when being used.

Locational input: For locational input, *travel planning* and *flight search* were mentioned. More specifically, when traveling with a navigation device you might not have an exact address in mind but instead just want to input a city, district or street. Addresses themselves can also be ambiguous with incomplete information, since street names for example are not unique.
Flight search was mentioned in connection with vacation planning. Here uncertainty can

[2]Google Scholar, https://scholar.google.com/

occur due to the fact that one might not have a specific price, traveling time or even goal in mind, and thus input options allowing for a range of alternatives for these factors were desired by the participants.

Multiple selection options: Most likely inspired by their academic background, the participants named *multiple choice questions* in exams and *scales in surveys* (usually Likert scales), where it is often difficult to express an opinion in numbers.

Mixed: For the following scenarios we did not find appropriate groupings and thus will simply list them. First, the participants mentioned *speech recognition*, as it is uncertain how to pronounce things best for the underlying algorithm to understand.
Next up, they named *portion input* on online cooking sites (every person might have their own understanding of "one portion") and *setting alarms* for e.g. cooking time, which might differ from kitchen equipment to kitchen equipment. The participants also mentioned *stock purchase*, as the stock market is filled with uncertainty.
Inspired by their math studies background, a participant mentioned *numerical precision* and *correct terminology* when writing a paper, and also *uncertain input parameters* for a math program.

4.5.2 Input Ideas for Uncertainty

In this section we present the ideas our participants came up with in order to enable the communication of uncertainty for their respective scenario.

Starting with the first group, their scenario consisted of the multiple and single choice tests. Their first idea was to have a hierarchical structure for the answers, meaning that the most likely answer receives a rating of 1, the second most likely a 2 and so on.
They also mentioned a different approach of independently evaluating the answers by giving each answer a "probability value" with differing amounts of crosses (could also be numbers) as follows: 3 means "certain", 2 means "likely", 1 means "unlikely", 0 means "definitely not".
Lastly, they mentioned the possibility of a textual explanation to express their uncertainty in detail.

The results of the search engine scenario are up next. Most likely due to the initiators' background in informatics, their first generated idea was the use of regular expressions for searching (for an explanation see [Tho68]). Although this is not a new idea, Google[3] for example only supports this feature in a very limited form of code search.
They also came up with the idea of defining word groups, meaning that similar expressions with similar semantical meanings (e.g. "apartment", "house", "flat") can be defined by the user to cover the uncertainty with a common denominator.
Also tackling the problem of ambiguity, they suggested that a search engine could cluster the

[3]Google, https://www.google.com/

results for each semantical meaning and present these clusters or alternatively ask the user for a more precise input when ambiguity is present.

This group was assigned the scenario of online form inputs, also including passwords. Their first proposal was that passwords should always be visible, instead of being represented by asterisks, in order to reduce uncertainty on password input.
For complicated forms they proposed small hints next to input fields on how or where to find the required information (e.g. "Where can I check my customer number?"). They also mentioned input validation, if possible, in order to reduce clearly wrong inputs, but also to give the user a sense of correctness (e.g. a customer number has a length of 10 characters and always starts with a 1).
On a similar note, "autofill" was suggested to be used whenever possible, either derived from inputs previously made or when required data is already stored on either the client or server.

The fourth group developed solutions for one of our scenarios, being calorie intake, as their original scenario posed redundancy to another group.
Their first idea was to abstract the exact weight of a product via using predetermined size classifications (e.g. "a big apple"). Similarly, amounts could be used for small food products instead of weight (e.g. "20 grapes").
They also proposed the use of barcode scanners for known products, as many applications already do in practice.

The last group examined the flight search scenario. They proposed inputs on constraints (e.g. flight time, vacation duration), but at the same time the possibility to input tolerance intervals (e.g. vacation duration of 5 to 7 days). They also proposed to give users control over their importance ratings on different aspects like time, price, etc. They visualized this using a graphical slider ranging from "do not care" to "very important".

4.5.3 Evaluating our Designs

In this section we present the feedback the participants gave us concerning our preliminary prototypes. Figure 4.7 shows pictures of the participants examining the different prototypes.

Spring Slider
On the positive side, the participants mentioned that using more pressure for more certain inputs feels intuitive and that it can be used using only one hand.
On the negative side, they found that the thumbs do not lock in place and thus it is unclear when the input is made. They also criticized the fact that only one interval can be input, and that this interval is limited by the range of the spring.

Split Slider
The participants rated the Split Slider as very intuitive, and also flexible because the different amounts of thumbs allow users to make inputs in line with their statistical knowledge, while at the same time it allows for quite detailed modeling of probability distributions. They also liked

(a) Expandable Dial **(b)** Spring Slider **(c)** Pressure Dial

Figure 4.7: Prototype Phase – Participants interacting and experimenting with our designs. Green papers were used to note down their findings.

the simple design, and that the interval size gives direct visual feedback on the uncertainty. On the other hand, some criticism was expressed because without a manual, it is unclear what the underlying probability distribution of the two and three thumb modes is.

Pinch Dial

Like for the Spring Slider, the participants mentioned that using pressure for certainty feels intuitive. They gave the pro argument that the Pinch Dial is very handy and compact and thus can be used with only one hand.
The biggest point of criticism for the Pinch Dial was the difficulty of pinching it after it was rotated (when the opening is no longer between thumb and index finger). Another problem mentioned was that when grasping something, one usually always applies some minor pressure on it. Finally, it was also unclear to the participants how much pressure represents which amount of uncertainty (e.g. what does it mean to pinch it 50%?).

Pressure Dial

The biggest advantage mentioned was that compared to the slider designs, the pressure dial can be rotated infinitely and thus is not limited to an interval. Also the looks were appealing and using the prototype was described as "a fun experience".
On the negative side, the invariant pressure resistance was criticized, which did not give a good haptic feedback of the uncertainty.
Mentioned improvements included a dynamic scaling for the rotation (rotating longer will increase the interval that results out of one full rotation) and the addition of audio feedback when pressing.

Expendable Dial

For the Expendable Dial we had two prototypes, one that could be squeezed and one that could be stretched. The squeezable design more popular among the participants, as they felt squeezing was more intuitive than stretching when expressing certainty. They also liked the visually pleasing design and the fact that it could be operated one-handedly.
A problem they detected about this design is the fact that when trying to input the uncertainty

by squeezing the dial, accidental rotational movements might occur. Also the size of the dial might require some adjustment do different hand sizes.

4.6 Discussion

In this section we discuss the results of the focus group and their meaning for our research.

4.6.1 Scenarios with Uncertain Input

First, we rule out the application scenarios which entail some degree of uncertainty, but are not suitable for the communication of uncertainty, e.g. because exact inputs are required.
This includes any form of *password inputs*, as including uncertainty for passwords would compromise security. Also personal information like *social security number* or *customer number* are unfit for communication of uncertainty, since each customer is assigned a unique number and slight modification to that number might yield an entirely different person. Similarly, complicated forms like *tax return* require exact inputs as they are invalid otherwise.
For all the above mentioned scenarios, elimination of uncertainty is required instead of its communication.

Although the *stock market* scenario includes many uncertainties which could most likely be used with our research in mind, we will not investigate into it any further due to its complicated economical nature, which can hardly be grasped within a mathematical realm only. We will also not look further into *numerical precision* or *correct terminology* when writing a paper and *uncertain input parameters* for math programs, as these are corner cases, seldom found among the general public.

Next, we look into scenarios that might profit of uncertainty communication but do not fit our research, as we are looking at communication of uncertainty using tangible interfaces for continuous functions only.
This includes *url endings*, as they are not well-defined. The entirety of (string-based) *search* scenarios also falls into this category, as string values are not continuous. That could be partially solved by using the initial string as a base value and having an uncertainty input on e.g. the levenshtein distance. However inputting the base value (search string) would still require at least a keyboard. *Speech recognition* entails very similar patterns to string search concerning uncertainty.
Since our research focuses on input with tangible interfaces tailored for this task, the scenario of using unfamiliar input devices like a *new mouse* is unsuitable for our research. However, it is included to some extend, since our input device will be unfamiliar for most users.

Finally, the scenarios that do fit our research will be presented. Almost identical in behavior with our application scenario for calorie intake, input on *body size and weight* fits right into this category. For the *flight search* scenario, the proposed idea of inputting e.g. price or vacation duration as intervals matches our solution ideas, which have two or more degrees of freedom. Also *scales on surveys* can be represented with a probability distribution instead of having deterministic quantified values. *Setting alarms* for e.g. cooking time could as well be input with uncertainty, in its simplest form by inputting a time interval. However, it has to be clarified exactly how the alarm audio output will behave during this interval.

Overall, the sheer amount of scenarios found by the focus groups within merely 10 minutes is a good indication for the assumption that people are aware of uncertainty within inputs, which also shows the relevancy of our research.

4.6.2 Input Ideas for Uncertainty

In this section, we compare the participant's ideas of how input with uncertainty could be handled to our ideas, in order to find similar solution approaches. Furthermore, we take a look at the ones that we did not mention.

Although the first application scenario, multiple and single choice tests, does not present continuous values and thus does not quite fit our proposed solutions for uncertain input, the proposal of giving each answer a "probability value" is nevertheless very similar to our approaches. Assuming our solutions with a continuous probability distribution, said distribution could be divided into small intervals, each with an averaged value, giving us a non-continuous distribution, and thus match the proposed solution of the focus group.

The problem and solutions of the search engine use case can hardly be transferred to the application scenarios and their respective solutions which we are interested in. However, they provide some similarities to other mentioned solutions. The idea of defining word groups is very similar to using predetermined size classifications like for calorie intake (see below), and asking the user for more precise input falls into the category of reducing uncertainty (see below).

The third group's ideas were more tailored towards how uncertainty can be avoided or at least reduced, as well as validating the inputs made. Of course these steps are important parts in handling uncertainty, however they are not within the extent of our research.

The ideas for calorie intake are discussed next. The mentioned size classifications for products can be seen as making inputs with predetermined probability distributions for each respective size classification. Similarly, the inputs with amounts would take a basic probability distribution for the product and stretch it with the amount parameter.

The final group, which was discussing the flight search scenario, came up with very similar designs to our research. Their idea to input tolerance intervals resembles our uncertainty input with lower and upper bounds. As they even mentioned GUI sliders, their proposal is a non-tangible version of our Spring Slider or Split Slider in two thumb mode.

Overall it becomes clear that solutions for the communication of uncertain input are manifold and that there is no single solution that fits all application scenarios. However, the fact that many proposed solutions are similar or convertible to our proposed ones, even though the use cases do not necessarily match, indicates a high likelihood for these solutions to be suitable for the problem.

4.6.3 Evaluating our Designs

Out of the designs we presented to the focus group, the Split Slider received the most positive review by a margin. On the other hand, the Pinch Dial was rated the worst, while the other three designs were on an equal footing, each with their own advantages and disadvantages.

In general, all dial designs suffered from the fact that the uncertainty input was disconnected from the value input (explicit uncertainty input), which was received worse by the participants, as they found it difficult to grasp what it actually meant for the value distribution. The slider based designs also entailed a minor common problem, being that their possible values are limited by slider size and thus they require a software scaling for inputs within different domains.

Due to its prominence in the focus group, we decided to implement a Split Slider prototype for the study.

5 Implementation

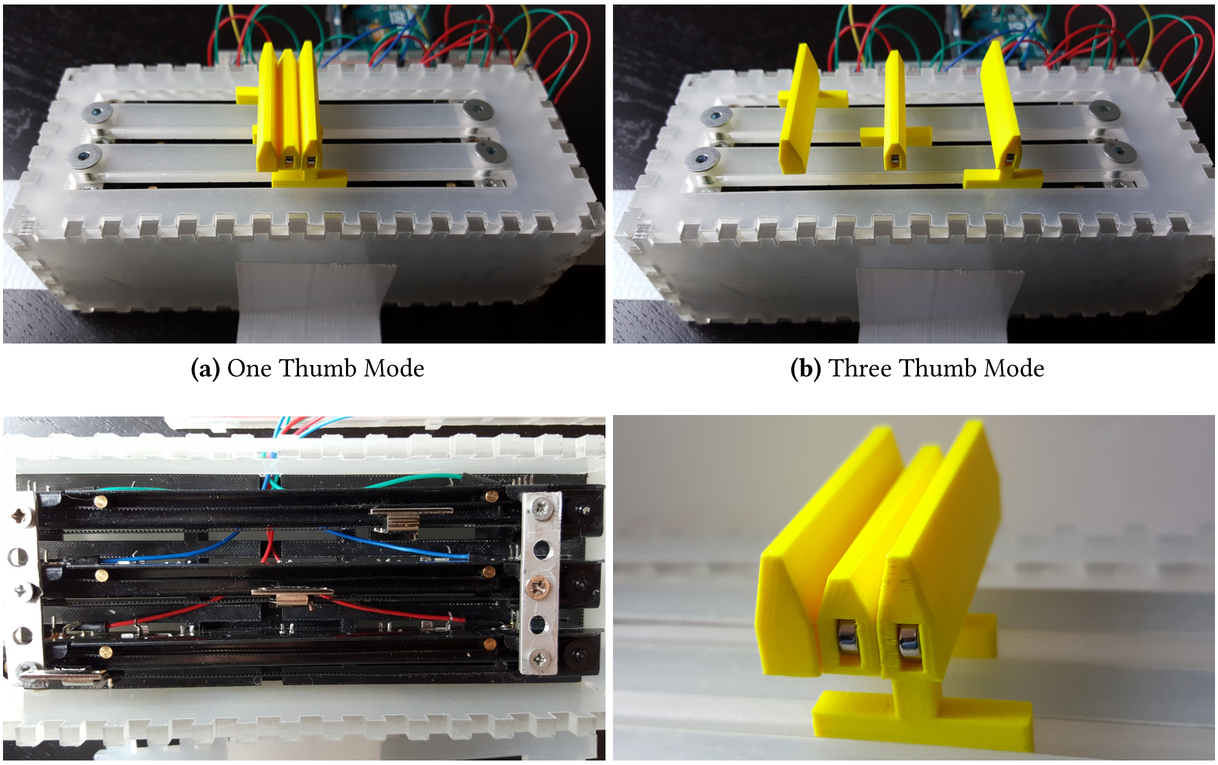
For the implementation of the Split Slider we used three slide potentiometers[1], an Arduino UNO[2] board, and a C++ program, using the *openFrameworks*[3] framework. In this chapter we present the constructed hardware and software in detail.

5.1 Hardware

The three slide potentiometers had a resistance between approximately 0Ω and $10k\Omega$. They were inserted parallely next to each other within a casing (see Figure 5.1c). With slider caps which reached each other (see Figure 5.1a and 5.1b) we evoked the illusion of our prototype being only one slider with three thumbs. All three thumbs together loosely formed a rectangle with a concave surface on top (see Figure 5.1d). This allowed for the three thumbs to be moved together by grasping the outsides, but allowed a finger to be placed in the gap on top, for easier splitting. Each individual thumb was formed like a rectangle with a spike on top in order to allow for an easy grip on the outside, but also to increase the gaps between the thumbs, which further improved the ease of using the splitting interaction. We used two small magnets on each adjacent side as a means of making the thumbs stick together when connected, since magnetism is a commonly known concept among users and also provides a splitting interaction that does not require an additional movement like our preliminary prototype did (see section 3.2.1). The magnets' strength was high enough to give users a perceivable haptic feedback of actually splitting them off, but as low as possible in order to make the splitting interaction convenient and to allow for small intervals.

On the Arduino board, we deployed the *standardFirmata* software without any modifications. We constructed a circuit from the 5V pin to the electrical grounding of the Arduino. In between we connected the three slide potentiometers in parallel. Each of the slide potentiometers was in a voltage divider circuit with a $4.7k\Omega$ resistor, relaying the voltage potential in between to the analog output pins. The analog output of the Arduino converts the incoming voltage (0V - 5V) into a 10bit number (0 - 1023). Since $\frac{R_{sp}}{R_{res}} = \frac{U_{sp}}{U_{res}}$ holds, the analog output values are within [0, 696). R_{sp} is the resistance of the slide potentiometer and R_{res} the resistance of the

[1]Bourns PSM Series Motorized Slide Potentiometer, http://www.bourns.com/docs/Product-Datasheets/psm.pdf
[2]Arduino UNO, https://www.arduino.cc/en/Main/arduinoBoardUno
[3]openFrameworks, http://openframeworks.cc/



(a) One Thumb Mode

(b) Three Thumb Mode

(c) Inside View

(d) Thumb Closeup

Figure 5.1: Split Slider Prototype – Implementation of the Split Slider design presented in section 3.2.1.

static resistor. Similarly, U_{sp} and U_{res} are the voltages for the slide potentiometer and resistor. We can calculate our slide potentiometer position P_{sp} using the following:

$$P_{sp} = \frac{1}{R_{sp}^{max}} R_{res} \frac{A_{sp}}{A_{max} - A_{sp}}$$

Whereas R_{sp}^{max} is the maximum resistance of our slide potentiometer, A_{sp} is the analog output of the voltage of the slide potentiometer, and A_{max} is the maximal analog output (1023).

Since our slider design did not provide any means of confirming the input, we used the spacebar key on an additional keyboard as input confirmation. However, for better and independent usability, a tangible solution is advised for future research (see chapter 7 for future directives).

5.2 Software

The C++ software handled all logic of our system. It was fed by the analog output values of the Arduino board. Due to the unstable nature of the values (which can be seen in Figure 5.2)

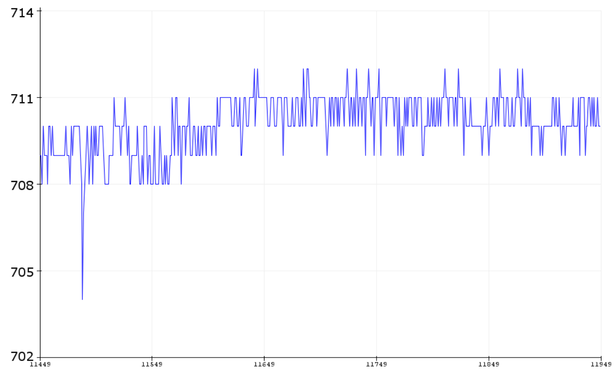


Figure 5.2: Potentiometer Noise – Diagram depicting the instability of the values (noise) as well as the imprecision, as the theoretical maximum value is 696.

produced by the sliders, Arduino, and circuit, we smoothed the input our software received by averaging the last 150 values for each slider, doing so in parallel threads running each 3.3µs. Additionally, since the minimum and maximum values of the sliders were different for each one due to imprecisions, we added a calibration phase. Within the calibration, we scaled the measured minimum and maximum values of the sliders to their theoretical bounds of [0, 696). The calibration was done in one thumb mode, so that all sliders returned approximately the same value when connected in one thumb mode. Listing 5.1 shows the code of the value update routine.

```
void Slider::updateRecentValues() {
	while (ofApp::dataCollectionRunning) {
		ofApp::arduinoAccess.lock();
		dataAccess.lock();
		if (arduino->isArduinoReady() && arduino->isInitialized()) {
			if (this->pin == 0) {
				arduino->update();
			}
			sliderValues[smoothIndex] = (float)arduino->getAnalog(pin);
		} else {
			sliderValues[smoothIndex] = -1.0;
		}
		if (++smoothIndex > SMOOTH_COUNT - 1) {
			smoothIndex = 0;
		}
		dataAccess.unlock();
		ofApp::arduinoAccess.unlock();
		std::this_thread::sleep_for(std::chrono::nanoseconds(INTERVAL_NS));
	}
}
```

Listing 5.1: Slider.cpp code excerpt - Code which updates the recent values received from the Arduino and stores them in an array for later calculations.

We used `arduinoAccess` as a mutex to ensure that only one thread at a time accesses the arduino and `dataAccess` to guarantee that no race conditions occurred within individual sliders while writing and reading data. Further, the constants had the values `SMOOTH_COUNT` = 150 and `INTERVAL_NS` = 3333, meaning that the actual input was delayed by 500µs, which is neglectable for interaction with humans.

During the implementation phase, we came to the conclusion that the two thumb mode is rather confusing, especially for users who do not know the precise meaning of it, since the visual representation of the maximum value suddenly jumps whenever the slider mode is switched between two thumb and three thumb mode. So we decided to remove the two thumb mode altogether and instead only differentiate between one and three thumbs. Achieving the same results as the two thumb mode is still possible by moving the second thumb exactly in the middle of the outer thumbs, but requires additional effort by the user.

6 Study

In this section we present the application scenario we chose for the study and the research goal on which we laid special focus. Following this, we present the study setup and procedure. In the end, we present the results and discuss them, and finally provide an answer to our research question.

6.1 Research Question

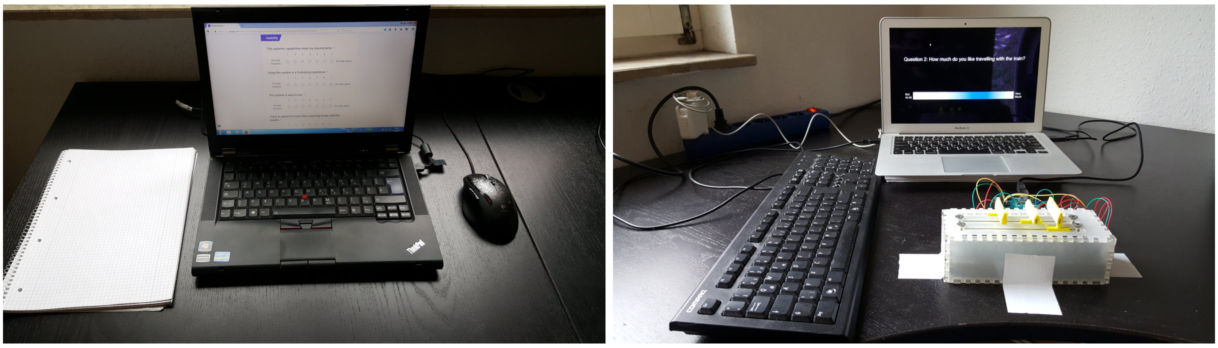
Based on the more general question of "are tangible user interfaces suitable for communicating uncertainty?", we define our research question RQ1, that examines whether our design is suitable for the communication of uncertain input, as follows:

RQ1: Is our slider design suitable for the communication of uncertain input?

6.2 Application Scenario

As already discussed in section 3.1, with the addition of newly found application scenarios from the focus group, we have a broad assortment of use cases at our disposal. In this section we evaluate the different application scenarios and finally chose the one that fits our research best.

Starting with the topic of calorie intake, this use case has a big upside due to preexisting correct data for comparison (weight of certain food items). Since most of these applications are used on mobile phones, it is unrealistic to assume that an input device the size of our prototype will be at hand, and if such a prototype was at home, scales would be as well. The use cases of search and shopping, which are very similar, both only work for a very limited subset of their actual use cases, being integer values. Also it is arguable why a tangible device should be preferable for these applications. Finally, ecological footprint and surveys can both be put into a public setting, which gives additional justification for using a tangible device (see 2nd paragraph of chapter 3.2). The topic of ecological footprint can be imagined in an environmental exhibit of a museum, whereas a survey could for example be installed within trains in order to get the opinions of their passengers. Although a strong case could be made for either of the last two scenarios, we decided to use a train survey scenario for our study, since asking participants about their ecological footprint might be intruding into their privacy.



(a) Questionnaires **(b)** Survey

Figure 6.1: Apparatus – On the left, people filled in their demographic data, questionnaires and a statistical knowledge test. On the right, the survey was answered using the prototype.

6.3 Method

We conducted an explorative user study with two conditions and two groups. The conditions were applied in a within-subjects design. The two groups consisted of 12 participants without previous knowledge and 6 participants with previous knowledge. The first six questions had to be answered under the first condition, being that no explanation of the prototype was given, but the participants were encouraged to experiment with it. The second condition was answering the questions after an elaborate explanation of the operating mode of the prototype.

6.4 Apparatus

For the input on our survey questions, the participants were seated approximately 40cm away from the prototype slider (for information on the prototype see chapter 5). The slider was fixed to the table, so that all participants had the same experience, but also due to the fact that the resistance of the three individual sliders was strong enough to slightly move the entire prototype. Since our slider did not include any means of input confirmation, we placed a keyboard left of it (rotated 90° counterclockwise) that could be used as confirmation by pressing spacebar. A 1440x900pt (28,7x18cm) monitor was positioned approximately 50cm behind the slider, displaying the survey. For the questionnaires we used Google Forms[1]. They had to be filled in by the participants on a separate laptop. The study setup can be seen in Figure 6.1. The two laptops were placed next to each other, so that participants could conveniently swap between the survey and questionnaires.

[1]Google Forms, https://docs.google.com/forms/

6.5 Task and Procedure

The participants were asked to do the following tasks, which had to be done in the given order:

- **Consent Form:** The participants had to sign the consent form, most notably including the right to drop out, guarantee of anonymity, and acceptance of video recording of their hands and the screen.
- **Demographic Information:** Each participant filled in a sheet with demographic information. We were interested in their gender, age, highest degree of education, work, and field of study/work, as well as previous experiences with graphical and physical sliders.
- **Introduction:** To start off the study, the participants were given a brief explanation of the study procedure, including the two survey phases, each followed by a questionnaire. For each participant, the slider was put into its basic position: all thumbs in the middle, connected.
- **First Prototype Usage:** The participants had to use the prototype to answer the first 6 survey questions (see below) without an explanation of the operating mode of the prototype, but were told to feel free to experiment with it.
- **First Qualitative Data Collection:** Afterwards, they had to fill in the questionnaire for the first time with their current understanding of the prototype.
- **Prototype Explanation:** The instructor explained the operating mode of the prototype to the participants. This included deterministic input with one-slider mode, the meaning of each individual thumb when split, and an example of how these options could be utilized.
- **Second Prototype Usage:** With the newly acquired knowledge of the prototype, the participants now had to answer the final 6 questions.
- **Second Qualitative Data Collection:** Following the second part of the survey questions, the participants now had to fill in the questionnaire again.
- **Statistical Knowledge Test:** Like in the focus group, the study closed with the Berlin Numeracy Test [CGS+12]. We assured the participants that this test was not meant to judge them, but to find possible relations between their statistical knowledge and results. This time we used a multiple choice variant with three questions, out of which two were new compared to the focus group.

Survey Questions:

For the first part we asked the participants different questions similar to how they could be found within a real train survey. In total, we presented them 12 different questions, each with a continuous scale and a lower and upper scale labeling. These included for example: “How

often do you use the train?" ("Never" to "Daily") or "How is the noise level in the trains?" ("Very Loud" to "Silent"). A detailed list of all questions with their respective response options can be found in the appendix (see section A.2).
In order to ensure that any possible variance in difficulty of the questions themselves did not influence our results, we used a 12x12 latin square design [Win62] to pseudo-randomize the question order for the participants.

Questionnaire:

The first four questions of our questionnaire were aimed at the usability of our prototype. Since we presented the same questionnaire, once for each phase, we deemed the "System Usability Scale" (SUS) [Bro+96], with its 10 questions, as too tedious and instead decided to include the "Usability Metric for User Experience" (UMUX) [Fin10], which has been proven to yield very similar results to the SUS. Since the scaling of the UMUX ranges from 1 (Strongly Disagree) to 7 (Strongly Agree), we designed all other questions to fit this scaling for the sake of consistency. The next two questions were concerning uncertainty. We asked the participants if they prefer to be able to input uncertainty, and also if the system feels more reliable when taking uncertainty into account. The final questions were tailored to our prototype. We wanted to know whether the participants think that the prototype is suitable for uncertain input, and also if they understood how to use the prototype. Afterwards they had to state if they would have liked to use any other input device instead, and if so, which one. Finally, they could give their opinion in form of a free text on whether there was anything about using the system that they particularly liked or disliked. All questions in their original formulation can be found in the appendix (see section A.2).

6.6 Participants

For the study we had eighteen participants. Twelve of them had never seen or heard of the prototype before, while the other six had prior knowledge of it. We had five female participants and thirteen males. The age of our participants ranged from 16 to 61 years ($M = 34.44, SD = 14.94$). With the help of a Berlin Numeracy Test [CGS+12] we gathered information on the participants statistical knowledge level. They scored an average of 1.67 ($SD = 1.01$), within the possible range of [0,3].

6.7 Results

In this section we present the results of the user study. Alongside the results of the questionnaire (see section 6.5), we also collected data on movement times, as well as on thumb positions for each question. Additionally, we collected trajectories and hand recordings in case of data

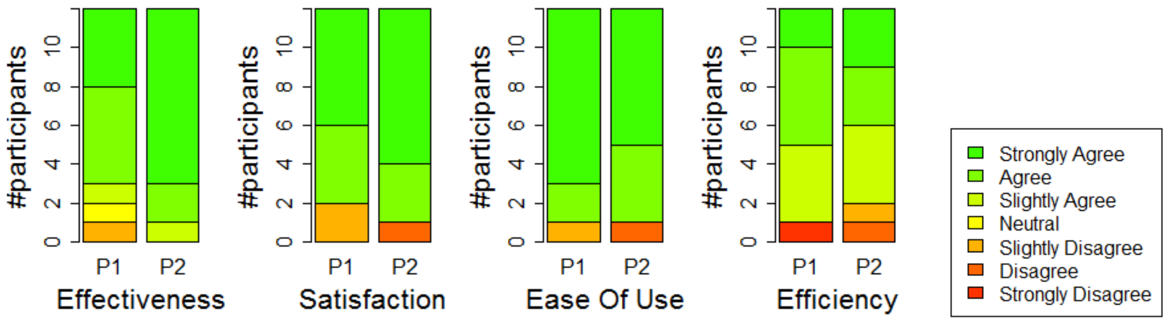
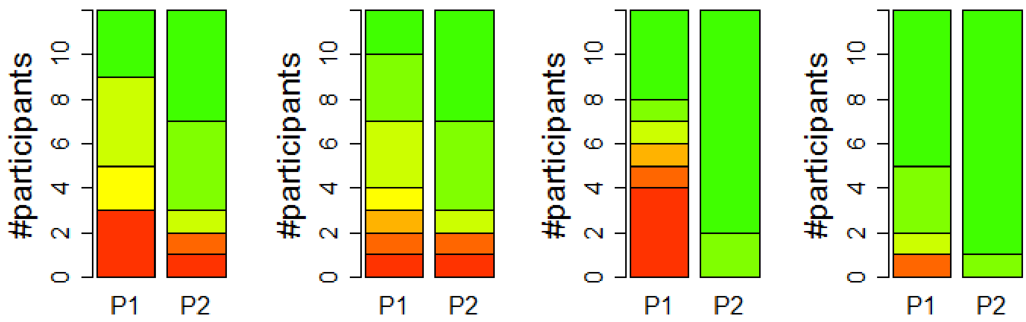


Figure 6.2: UMUX Results – User responses of participants without previous knowledge to the individual UMUX questions for phases P1 and P2. Results on satisfaction and efficiency have been inverted, as they were formulated negatively. Exact formulations of the questions can be found in the appendix (see section A.2).



(a) Uncertainty Preference **(b)** System Reliability **(c)** Prototype Suitability **(d)** Prototype Understanding

Figure 6.3: User Responses – User responses of users without previous knowledge to uncertainty and prototype questions for phases P1 and P2. Exact formulations of the questions can be found in the appendix (see section A.2).

anomalies or interesting findings. Each of the eighteen participants had to answer twelve questions, so we collected a total of 216 trials.

6.7.1 User Feedback

Usability: The usability of our prototype was evaluated using UMUX. Taking results from both phases of all participants into account, our prototype reached an UMUX score of 82.41 ($SD = 17.00$) out of [0,100]. For participants without previous knowledge, the UMUX score was 82.29 ($SD = 17.51$) in the first phase, with a minor increase to 85.76 ($SD = 19.17$) for the second phase (see Figure 6.2 for responses on individual questions). The Friedman test yielded no significant difference for the effect of knowledge on the usability ($\chi^2 = 0.818$, df $= 1$, $p = 0.366$). The major points of criticism given in the qualitative feedback were the deficient smoothness of the thumb movements and the magnets, preventing input of tiny intervals, as well as making the splitting more difficult.

Uncertainty Preference: On the matter whether the participants (without previous knowledge) preferred to be able to input uncertainty, there was a noticeable increase from phase 1 ($M = 4.33, SD = 2.27$) to phase 2 ($M = 5.58, SD = 2.02$) within the possible domain of [1,7] (see Figure 6.3a for detailed results). This change was statistically significant, as determined by a Friedman test ($\chi^2 = 5.444$, df $= 1$, $p < 0.05$).
Among all eighteen participants, there were three, who absolutely disliked the idea of uncertain input. The reasons given were that it takes too much time, that the stepless nature of the scale feels imprecise and that it seems unnecessary altogether.

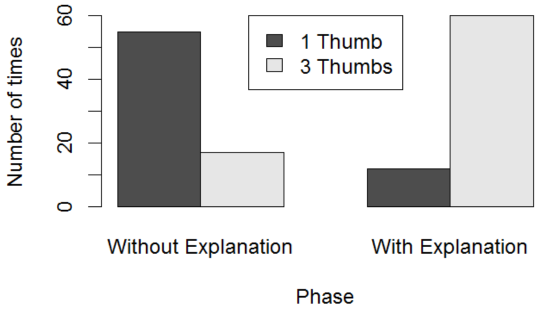
System Reliability: Similar answers as for the previous questions were obtained for the question if the system felt more reliable when taking uncertainty into account. Although the Friedman test yielded no statistical significance ($\chi^2 = 2.0$, df $= 1$, $p = 0.157$), the values increased from phase 1 ($M = 4.75, SD = 1.91$) to phase 2 ($M = 5.58, SD = 2.02$) within the domain of [1,7] (see Figure 6.3b for detailed results).

Prototype Suitability: The prototype's suitability for uncertain input in phase 1 was rated slightly above average ($M = 4.00, SD = 2.73$) by participants without previous knowledge. After the explanation, this rating increased significantly ($\chi^2 = 7.0$, df $= 1$, $p < 0.01$) to 6.83 ($SD = 0.39$) within the realm of [1,7] (see Figure 6.3c for detailed results). In the qualitative feedback section, one participant responded that it "perfectly fits the task." Two participants would have preferred to be able to add an additional textual input to answer certain questions in more detail.

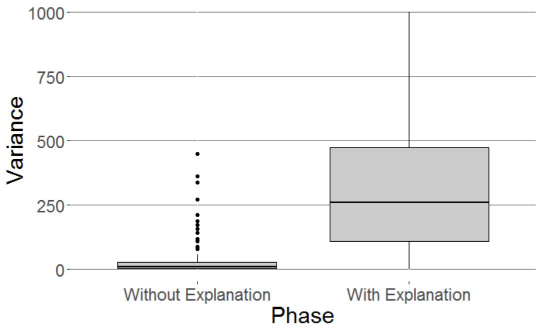
Prototype Understanding: The final Likert scale question was concerned with the comprehension of the usage of the prototype (see Figure 6.3d for detailed results). Within the interval of [1,7], the participants without previous knowledge rated their understanding in the first phase as 6.17 on average ($SD = 1.47$). With the newly gained information in phase 2, they rated their understanding slightly higher with 6.92 ($SD = 0.29$). As determined by a Friedman test, this change was significant ($\chi^2 = 5.0$, df $= 1$, $p < 0.05$).

6.7.2 Prototype Usage

Splitting Behavior: Figure 6.4 shows how often the different thumb modes were used in the two phases for participants without previous knowledge, and how much variance (uncertainty) between the outer thumbs was expressed. While in the first phase participants used the one thumb mode more than 3 times as often as the three thumb mode (55 vs. 17), knowledge about the prototype strongly shifted this ratio to approximately $\frac{1}{4}$ (12 vs. 60). A chi-square test of independence was performed to examine the relation between previous knowledge and slider mode usage. The relation between these variables was significant ($\chi^2 = 49.237$, dt $= 1$, $p < 0.001$). Similarly, the expressed variance increased drastically from phase 1 ($M = 47.44, SD = 90.34$) to phase 2 ($M = 303.39, SD = 249.16$). The variance represents



(a) Thumb Mode Usage



(b) Expressed Variance

Figure 6.4: Splitting Behavior – Influence of knowledge about the prototype on the usage of the different thumb modes (left) and the expressed variance (right). The data only includes participants without previous knowledge.

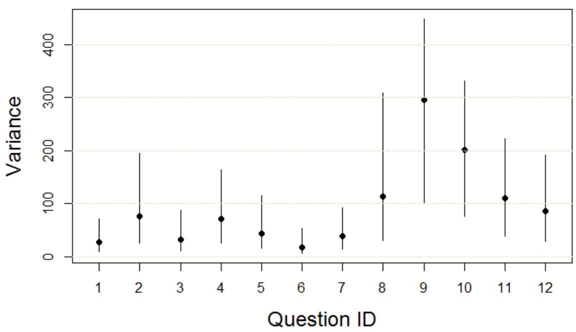
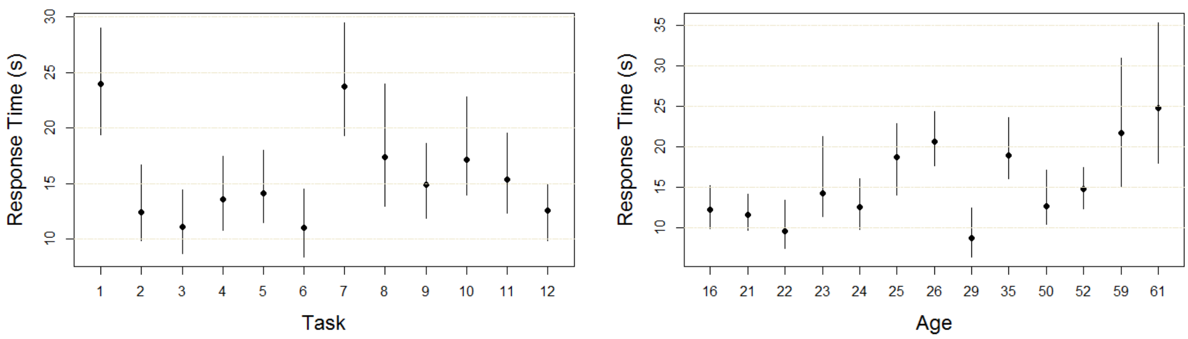


Figure 6.5: Question Variance – Influence of the individual questions on the expressed variance for all participants. The detailed question catalog can be found in the appendix (see section A.2).

the distance between the outer thumbs and thus the uncertainty, and is within the domain [0,1000]. This difference was statistically significant between groups as determined by an independent 2-group t-test ($t(89.352) = -8.1942, p < 0.001$).

Question Uncertainty: Next, we were interested in whether the different questions yielded different expressed variances, meaning that participants were more uncertain. Figure 6.5 shows the expressed variance subject to the question id. The data includes all participants. Since the data did not meet assumptions on sphericity and homogeneity, we applied the ARTool provided by Wobbrock et al. [WFGH11] to our data. With a one-way repeated-measure ANOVA, we found a significant effect of the question on the expressed variance ($F(11, 187) = 3.987, p < 0.001$). Post hoc pairwise comparisons yielded significant differences between the following questions (left less, right more expressed variance): 1:9, 1:10, 3:9, 6:8, 6:9, 6:10, and 7:9 (see section A.2 for question specifics).



(a) Learning Curve

(b) Age Curve

Figure 6.6: Response Times – Influence of practice and age on the response time.

Learning Curve: Figure 6.6a depicts the response time of participants in dependence of previous practice. We found a weak correlation between previous practice and response time for phase 1 ($r(106) = -0.293, p < 0.01$) as well as for phase 2 ($r(106) = -0.295, p < 0.01$), meaning that the expected response time is lower with each additional use. This effect is not unusual, as a learning curve is to be expected when exposing users to something new.

Age Influence: There was also an expected result in the positive correlation between age and response time ($r(214) = 0.215, p < 0.01$), depicted in Figure 6.6b. In general, the average response time increases with age, which is an observation often found within the domain of HCI experiments.

Uncertainty Response Times: Looking at the time participants needed to answer questions, results show that entering one deterministic answer ($M = 11.96s, SD = 7.26s$) took approximately half the time of making uncertainty inputs with the three thumb mode ($M = 21.24s, SD = 11.63s$), which was to be expected.
Upon closer inspection, we found a weak correlation between the expressed variance and response time ($r(214) = 0.345, p < 0.001$). Figure 6.7 depicts the response time in relation to the variance. We calculated a simple linear regression to predict the response time based on variance. A significant regression equation was found ($F(1, 214) = 28.89, p < 0.001$), with an R^2 of 0.119. A participant's predicted response time is equal to $14.31 + 0.014\ (variance)$ seconds, when variance is measured within [0,1000], meaning that with increased uncertainty the expected response time increases as well.

6.8 Discussion

In this section we will discuss the results and make conclusions as to what they mean for our research.

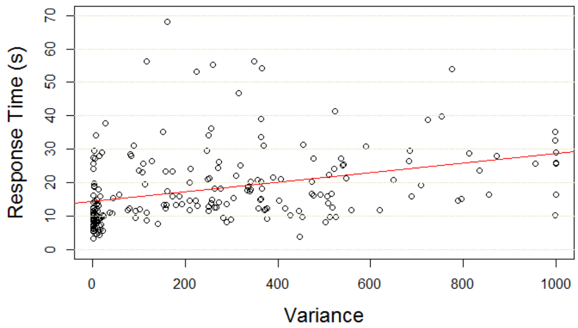


Figure 6.7: Uncertainty Delay – Influence of uncertainty (variance) of all participants on the time they needed to answer a question.

Considering how differently participants used the prototype in the two phases, it can be concluded that the usage of the prototype is not self explanatory, since the majority of participants without previous knowledge did not use it as intended without an explanation. While the criticism given to the lack of smoothness of the thumbs is simply a prototype flaw, the problems described about the magnets, are a design flaw. Further investigation might yield alternative options (see chapter 7) for splitting or even deem the haptic feedback unnecessary.

The ratings on the UMUX score show that using the prototype in three thumb mode was not perceived significantly worse by the participants with regard to usability, compared to using it in (mostly) one thumb mode like a traditional slider. Thus, we can conclude that the usability of three separate thumbs is similarly as good as that of one thumb, which represents a traditional slider. Taking the research of Bangor, Kortum, and Miller [BKM09] into account, who investigated results on SUS scales and quantified them with adjectives, we can interpret the usage rating of our prototype as *excellent*, since the UMUX score strongly correlates with SUS.

The results on preference for the possibility of uncertain input show that most participants in phase 1 would have preferred to be able to input uncertainty. However, after they could experience it in phase 2, they appreciated it even more. The results also indicate a similar behavior for the perceived reliability of the system when taking uncertainty into account. From this, we can assume that either participants were unsure about the meaning or the benefits of uncertainty, or about how it could be expressed, or that they were positively surprised by the ease of inputting uncertainty with the prototype.

As the results have shown, the prototype has been perceived as very suitable for uncertain input, leading to a positive answer to our research question. However, as a participant stated that it perfectly fits the task, one also has to keep in mind that for other tasks it might not be (as) suitable. Also the demand for textual input to certain questions shows that uncertainty can not always be expressed in a numerical fashion. Nevertheless, the results show that the Split Slider design is a step in the right direction of uncertain input communication.

While most participants (without previous knowledge) thought they understood how to use the prototype, less than half actually used it as intended before the explanation. This shows that new interactions in an otherwise common device need to be clearly communicated, as most users did not experiment, but instead resorted to their previous knowledge on sliders. Similarly, it indicates that users are so accustomed to deterministic inputs that they do not think beyond. They did not experiment with the design, even though they were encouraged to do so, and also were informed that the study is about the communication of uncertainty.

Looking at the results of the expressed variance on the individual questions, we can see that the uncertainty vastly differed based on the question. To take a more detailed look, the questions themselves provide further clarification. The three questions (1, 3, 6), which had low variance in their answers are all based on personal train usage, and thus mostly depend on the user. On the other hand, the questions with high variance (8, 9, 10) were all based on trains, and hence depend on the collective of trains that each participant has used. Importantly, this means that participants did not just use uncertain input for the sake of making use of the possibility, but instead actually made use of it to the degree it was appropriate for the respective questions.

The results on response time relative to expressed variance give a good indication that the more uncertain users are about their input, the more time they require to think about and enter it. On the one hand, this improves our previous observation that the participants actually thought about the uncertainty input and used it appropriately. On the other hand, this result suggests that unusually long response times can be leveraged as indications for uncertainty.

7 Conclusion and Future Work

While previous work had shown that people prefer the communication of uncertainty in weather forecasts, it was still unclear whether this preference also applies to uncertainty about inputs. In this thesis we provided literature review on uncertainty, tangibility, and shape-change and presented several application scenarios where users are likely to be met with uncertainties about their input.
We proposed a total of nine low-fidelity shape-changing tangible interface designs, which support numerical inputs with uncertainty. With the help of a prestudy in form of a focus group, we narrowed down our designs to the most promising one. The results of the prestudy also indicated that users are indeed aware of different uncertainties accompanying their inputs. We constructed the Split Slider, rated best by the focus group, and gave insights into the detailed design and its implementation.
Finally, we conducted an explorative study with the focus on our research question whether the Split Slider is suitable for uncertain input.

Our research question was answered positively. The participants rated the suitability for uncertain input with an overwhelming score of 6.83 on a 7 point Likert scale. Similarly, the usability was rated excellent.
The results also showed that most of the participants did in fact prefer to have the possibility of uncertain input. This preference could be observed to an even greater extend after they had experienced the possibility of uncertain input using the Split Slider. They also stated that the system feels more reliable when taking uncertainty into account. The participants expressed their uncertainty when appropriate and reverted to deterministic inputs whenever they were certain. This shows that they were aware of the meaning of their uncertainty input and did not simply exploit the possibility.

For future directive, we propose that any mechanism providing uncertain input should also provide the possibility of deterministic input. For the deterministic input it is even more important that it is easily understandable, as our study showed that participants reverted to what they know about similar input devices when unsure about the usage. Even though the majority of participants needed an explanation of the prototype before using it as intended, this effect will increasingly fall off in case uncertain input devices become more prevalent. Additionally, future work might improve the intuitiveness of uncertain input devices.

This further development could include improvements to the Split Slider as well as the exploration of new designs for uncertain input mechanisms. Improvements to the Split Slider could be achieved through investigation into a tangible way of input confirmation. One possible

approach is an additional button on the prototype or the possibility to push the thumbs downwards. In addition, improvements to the splitting interaction are required, as the user responses showed that our magnet solution was suboptimal. On topic of the splitting interaction, better visual representations of new affordances are required, so that users can make them out on their own.
For further research on different designs we have already proposed a variety of possible tangible input devices. While the explorative designs provide powerful devices in terms of input modeling precision, dial and slider-based designs are more familiar to potential users as they have already found their way into the assortment of common input devices. There are of course many more possible designs as this research field is scarcely explored, and our design exploration only scratched the surface of shape-changing tangible input possibilities.
In addition, we limited our research to scenarios with continuous values. As the prestudy has shown however, there is also a vast range of application scenarios with uncertainty that do not provide continuous uncertainty values. Therefore, further research might also explore input mechanisms that allow uncertainty communication for these application scenarios.

In the grand scheme of things, we have shown that the communication of uncertainty is a field worth of further investigation. The results of our prototype also provided evidence that shape-changing tangible interfaces are one suitable solution for this task.

A Appendix

We present the questionnaires handed out to the participants of the focus group and study. All material is in its original language.

A.1 Focus Group

Berlin Numeracy Test

Von 1.000 Leuten in einer Kleinstadt sind 500 Mitglied im Gesangsverein. Von diesen 500 Mitgliedern im Gesangsverein sind 100 Männer. Von den 500 Einwohnern, die nicht im Gesangsverein sind, sind 300 Männer.

Wie groß ist die Wahrscheinlichkeit, dass ein zufällig ausgewählter Mann ein Mitglied des Gesangsvereins ist?
Bitte geben Sie die Wahrscheinlichkeit in Prozent an.

%

Stellen Sie sich vor, wir werfen einen gezinkten Würfel (6 Seiten).

Die Wahrscheinlichkeit, dass der Würfel eine 6 zeigt, ist doppelt so hoch wie die Wahrscheinlichkeit jeder der anderen Zahlen.

Von 70 Würfen, bei wie vielen dieser 70 Würfe würde dieser Würfel erwartungsgemäß eine 6 zeigen?

A.2 Study

Questionnaire

* Required

Participant ID

1. **Please enter your ID.** *

Usability

2. **This system's capabilities meet my requirements.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Strongly Agree

3. **Using this system is a frustrating experience.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Strongly Agree

4. **This system is easy to use.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Strongly Agree

5. **I have to spend too much time correcting things with this system.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Strongly Agree

Uncertainty

6. **I prefer to be able to input uncertainty.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Strongly Agree

7. **The system feels more reliable when taking uncertainty into account.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Strongy Agree

Prototype

8. **The prototype is suitable for uncertain input.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Strongly Agree

9. **I understand how to use the prototype.** *
Mark only one oval.

	1	2	3	4	5	6	7	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Strongly Agree

10. **I would have liked to use another input device.** *
If you would have liked to use another input device, please let us know which one.
Mark only one oval.

⬭ No
⬭ Other: ____________________

Other

11. **Is there anything you particularly like/dislike about using this system?**

Survey Questions

Question	Left Option	Right Option
1. How often do you use the train?	Never	Daily
2. How full is the train in general?	Empty	Very Crowded
3. How much do you like traveling with the train?	Not At All	Very Much
4. How do you perceive the hygiene within trains?	Very Dirty	Very Clean
5. How secure do you feel in trains?	At Risk	Very Safe
6. How do you find train ticket prices?	Very Cheap	Very Expensive
7. How is the comfort of the train chairs?	Very Uncomfortable	Very Comfortable
8. How do you perceive the noise level in the trains?	Very Loud	Silent
9. How is the timeliness of the trains?	Always Late	Always On Time
10. How fast do you get to your destination using the train?	Very Slowly	Very Fast
11. How reliable do you perceive the arrival time displays?	Very Unreliable	Very Reliable
12. How modern do you find the trains?	Very Old-Fashioned	Very Modern

Statistical Knowledge Test

Please answer the questions below. Do not use a calculator but feel free to use a scratch paper.

* Required

1. **Please enter your ID.** *

2. **Question 1**

   Imagine we are throwing a five-sided die 50 times. On average, out of these 50 throws how many times would this five-sided die show an odd number (1, 3 or 5)?

   Mark only one oval.

   - 5 out of 50 throws.
   - 25 out of 50 throws.
   - 30 out of 50 throws.
   - None of the above.

3. **Question 2**

   Out of 1,000 people in a small town 500 are members of a choir. Out of these 500 members in the choir 100 are men. Out of the 500 inhabitants that are not in the choir 300 are men. What is the probability that a randomly drawn man is a member of the choir? Please indicate the probability in percent.

   Mark only one oval.

   - 10%
   - 25%
   - 40%
   - None of the above.

4. **Question 3**

   In a forest 20% of mushrooms are red, 50% brown and 30% white. A red mushroom is poisonous with a probability of 20%. A mushroom that is not red is poisonous with a probability of 5%. What is the probability that a poisonous mushroom in the forest is red?

   Mark only one oval.

   - 4%
   - 20%
   - 50%
   - None of the above.

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All links were last followed on April 24, 2017.

Declaration

I hereby declare that the work presented in this thesis is entirely my own and that I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

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