Computational Design of Input Methods

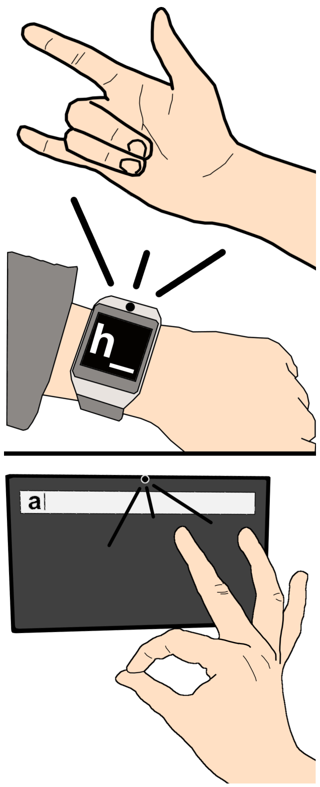

Figure 1: In my thesis I develop methods for computational design to optimize input methods for varying objectives, such as performance, learnability or ergonomics. I apply these methods for example to optimize the design of multi-finger gestures for fast and comfortable text entry in mid-air.

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Abstract

Designing a user interface or input method requires to evaluate and trade-off many criteria. The corresponding design spaces are huge, making it impossible to consider every potential design. Therefore, my work focuses on the use of *computational* methods for the design of input methods. I follow a modeling-optimization approach: understand and model the characteristics of the interaction, formulate the design space and develop (multi-) objective functions to evaluate designs, and develop algorithms to systematically search for the best design. In my projects I applied this approach to develop better text entry methods. Among others, I modelled the performance and anatomical constraints of the hand to computationally optimize multi-finger gestures for mid-air input, and studied how people type on physical keyboards, in order to understand and model the performance of two-hand typing.

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Context and Motivation

Advances in new sensing technologies, such as markerless hand tracking, EMG-based systems or eye tracking, open up the design space of input and enable designers to develop more intuitive and efficient user interfaces. However, it also increases the already large design spaces and presents us with complex problems, such as how to design intuitive mid-air gestures for input on a TV or how to efficiently enter text on a smart watch. As a result, designers explore these design spaces only sparsely, for example by using elicitation studies (e.g. [13, 16]) or by recreating existing designs (such as Vulture [10] or Zoomboard [11]). Thus, new input methods do not make optimal use of new sensing capabilities, neither of the human motor and cognitive capacities.

It is rarely realized, that many problems in HCI are combinatorially hard. For example there is no efficient algorithm that finds the best assignment from letters to the keys of a keyboard, not even within weeks or months of computing

Models and Methods used in text entry optimization

1. Fitts' Law is used to model input performance on virtual keyboards operated by one finger or stylus [9]. Approaches differ in the optimization methods they use, such as variants of *local search* [4, 17] or *integer programming* [7]

2. More complex input strategies require other performance models than Fitts' Law. Models have been developed for entering text with two thumbs [12] by extending Fitts' Law with a factor for hand alternation, and also for full ten finger text entry by averaging the intervals between key presses [6].

3. Multi-objective functions do not only consider finger travel time, but optimize a keyboard for different aspects of performance (e.g. for speed, familiarity and improved spell checking [3]), for multiple languages [1], or technological factors, such as better recognition of input gestures [14].

time. The problem becomes even harder if we open up the design space to consider not only input by button presses but allow any kind of hand and finger movements. Computational optimization is an algorithmic approach that can help to systematically explore these large design spaces and find good designs within a reasonable amount of time and without having to rely on expensive elicitation studies or empirical user tests. They use quantitative models to generate and evaluate millions of designs. This allows us to easily investigate the potential impact of new design principles or technologies.

Optimization in HCI has mainly been used to find optimal keyboard layouts. In my work I want to expand the application of this method to the input itself and optimize the *performance of manual input methods*. Here, performance is not only defined in terms of finger travel distance or operation time, but takes into account a broader range of factors which eventually influence the speed of input, such as ergonomics and anatomical constraints, learning time, or technical limitations. I particularly focus on *text entry*. While text entry methods have been studied and developed for nearly 100 years, entering text is still the interaction bottleneck of most computing devices. However, it is a well-defined problem with concrete performance metrics and solutions to compare to and therefore well suited for testing new approaches to design. On the other hand, the problem is too complex in order to be investigated manually, and thus a perfect candidate to show the benefits of the optimization approach to design.

Background and Related Work

In the last years, computational optimization has gained increased interest in HCI, with first applications in text entry. The problem of assigning the letters of the alphabet to the keys of the keyboard, the so called *letter assignment problem*, has been recognized in the field of operations research already in the 1970's. It has been found to be a special case of the quadratic assignment problem and therefore to be NP hard [2]. Since then, many mathematical and algorithmic approaches have been developed to approximate good solutions [8].

While these solutions can be applied to find good designs in a reasonable time, there remains a challenge for HCI to formulate the objectives for optimization, that is the to-be-optimized function that quantifies the goodness of a solution. This has been the focus of text entry research considered with the optimization of virtual keyboards in the last decade. There, the goal is to model different aspects of input and implement these models in an objective function that can be used for optimization. A selection of applied models and methods are listed on the left of this page.

My thesis builds on the achievements on solving the letter assignment problem. However, the design space of manual input opens up when introducing new design principles or sensing technologies, such as camera or electromyography based gesture recognition. To make optimal use of these advances, we need to rethink the standard input paradigms and consider the units of input themselves. Thus, in my research I develop new models and methods that are more broadly accessible and usable across different input methods and sensing technologies to solve problems beyond the letter assignment problems for virtual keyboards.

Research Goals and Methods

The goal of my thesis is to develop methods for the computational design of input methods, in particular for text entry. Therefore I want to establish an optimization approach to design that allows to systematically explore the large design spaces and optimally implement design criteria that

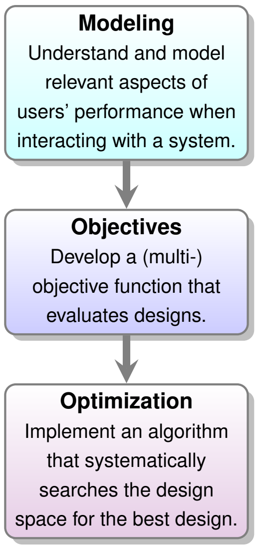

Figure 2: Modeling-optimization approach: it describes the steps necessary to apply computational optimization to the design of input methods. In my thesis I follow this pipeline in multiple cases, where I investigate the impact of new design principles and technologies on performance and other factors.

maximize the given objectives. In contrast to prior work, my research will go beyond the optimization of keyboard layouts and rethink the units of input themselves, including the movements performed by hands and the controlled elements of the input device. Moreover, I want to make the optimization approach to design more accessible and expand the application of models and algorithms to a broad range of input methods, not only to text entry.

There are several challenges that need to be addressed in order to make computational optimization applicable to the design of input methods:

1. **Modeling**: How can we capture the different aspects of interaction from the human as well as system side in models that are fast to evaluate?
2. **Objectives**: What are the objectives relevant for design and how can they be quantified in terms of the available models?
3. **Optimization**: How can we formulate design spaces to computationally generate designs, and what computational methods are needed to explore the design space, taking into account multiple objectives and the uncertainty of the input data.

Based on these challenges I have constructed a *modeling-optimization* approach which constitutes the methodology of my work and at the same time defines the steps necessary for using optimization as an approach to design. In my work I apply and contribute to the different steps of this approach in several design cases, investigating new technologies, design principles, and different factors of text entry. Example cases and the research questions related to them are:

1. **Transfer of expertise:** Can we transfer a user's expertise with a system to maximize performance with a new input method and allow for better adaptation?
2. **Mid-air input:** How can we design mid-air gestures that make optimal use of the many degrees of freedom of the hand? Which hand gestures are fast and easy to perform and what is the optimal way to assign them to interface controls?
3. **Optimal input strategy:** What are the factors related to fast performance on physical keyboards? How do people type in their everyday computer usage and is there an optimal strategy for fast text input?

After the doctoral consortium I hope to extend this list based on feedback and discussions with others, and hope to find collaborations to apply these methods to the computational design of other user interfaces.

Dissertation Status

Dissertations at my university are commonly submitted in form of a collection, where the written part only consists of an introduction accompanied by a collection of publications. This allows me to focus on publishing my contributions in form of papers. In my projects described below, I followed the methodology described in Figure 2 to varying extents, contributing to different parts of the approach, with the overall goal to develop better ways to enter text.

Expertise transfer: In the first case we maximized performance of a piano-based text entry device by optimally transferring the motor expertise of a pianist to text entry [5]. We created a quantitative model of a pianists' motor skill based on statistics of music and developed an algorithm that constructed a mapping from language to music that makes optimal use of this expertise. A long-term study over 140 hours showed performance rates of over 80 words per minute, at a learning time *half* of that required for the Qwerty keyboard.

Mid-air input: In my second project, we developed a new way to enter text in mid-air by **optimizing multi-finger gestures** [15] (Figure 1). We modelled the performance and anatomical constraints of finger motions to optimize the design of gestures and their mapping to the letters of the alphabet. The observed performance rates surpassed existing methods and the obtained models and methodology are applicable to the design of any system that uses mid-air gestures.

The findings in both cases are very promising and show the success of the optimization approach. We could not have achieved similar results with manual design approaches. In particular, tasks such as high performance text entry are too complex and too abstract in order to achieve good designs with traditional design methods. Moreover, the obtained models and methods are applicable beyond text entry and can inform the design of any input method.

Input strategy: In our most recent work we wanted to understand the factors that influence performance in everyday typing on physical keyboards. In contrast to prior work that tries to optimize the input device, our ultimate goal is to optimize the input strategy to efficiently interact with the given device. Towards this question we conducted a motion capture study capturing the hand and finger movements of people while typing on a physical keyboard. Beyond the touch typing system, we could identify several different movement strategies. Surprisingly, we found that the number of fingers was not predictive of typing performance. Instead we found several other factors that allowed for fast typing, such as motor preparation and minimized global hand motion.

Large real-life problems: Currently, we are working together with the French standardization committee to optimize a new keyboard layout for the French language, focusing on the optimal arrangement of more than 100 special characters (punctuation marks, diacritics, characters of foreign languages, etc.). The goal is to design a keyboard layout that allows easy, fast and ergonomic input of the french language, while providing an intuitive keyboard that retains similarity to the tradititonal Azerty layout. To find the best possible design among the 10^196 alternatives, we propose to combine optimization methods with expert design knowledge in an interactive workflow.

For future work, I am interested in using computational methods of optimization and machine learning to find an **optimal movement strategy** for typing. Moreover, I want to use those methods to design an **optimal training program** that allows a user to maximally improve their self-taught typing strategy within minimal training time.

Expected Contributions

The goal of my thesis is to establish computational design, such as optimization, as an approach to the complex design of input methods. To this end my thesis will contribute:

1. models of performance, ergonomics, and other factors related to input,
2. novel multi-objective functions as metrics for input,
3. algorithmic approaches for the optimization of input methods.

While the focus of my thesis is on manual input by discrete selections, in particular text entry, the results will contribute to the design of any input method and will show the potential of computational design of user interfaces.

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