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Making sense of haptics

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Chapter 1

Introduction

There are many environments in which it is not practical to do things with your own hands directly. For instance, it is not wise to enter a nuclear plant to perform device maintenance. In that case, it would be smarter to position robots inside the plant that can be directed by the maintenance worker outside of the plant. Another example is a keyhole procedure in surgery. In this procedure, instruments are inserted into a patient through tiny holes, to avoid large wounds in relatively simple procedures. The surgeon could use his own hands to guide the tools, but quite often, the surgeon actually uses a joystick to guide a robot to insert the tools, because this enables him to scale his movements to small and precise movements inside the patient. So, both the maintenance worker and the surgeon use teleoperation systems: systems consisting of a *master*, which is the interface (such as a joystick) that is used by a human (from now on called *operator*), and a *slave*, which is the robot that is performing the action in the remote environment (Srinivasan & Basdogan, 1997). Obviously, there are large advantages to teleoperation techniques for the operators: the maintenance worker in the nuclear plant is not exposed to radiation and the surgeon has a far better view of his patient, because his hands are not in the way. However, there is also at least one large disadvantage to this technique: since the master and the slave device are usually not directly connected, the operator cannot directly feel what the slave is doing. When he would be performing the task with his own hands, he could have used sensory information from his hands, also called *haptic perception*, to feel what the slave is doing. To solve this problem, haptic feedback can be incorporated in the master device, which is the virtual equivalent of natural haptic information.

The aim of this thesis is to investigate parameters in haptic perception that are important for designing haptic devices and haptic feedback. This is done by using a deductive approach: fundamental properties of haptic perception are investigated, which can be applied to the design of specific haptic devices later on (Kimmig, 2013). Haptic device designers usually take the inductive approach: by testing the performance of their specific devices in user studies, they obtain general guidelines on which device parameters ensure satisfactory human performance (Heit, 2000). However, when doing this, it is hard to understand why certain approaches work and others do not, which limits the generalizability of the findings. Therefore, this thesis intends to provide the fundamental knowledge that is needed in order to solve these questions from a deductive perspective. This is done by answering questions like: if humans move their hands, how precisely can they perceive the distance that they have covered? The answers to these questions provide fundamental knowledge on haptic perception, which can be used in the design of a whole range of devices.

1.1 Teleoperation

When performing precise operations, there are two important sources of information: what you see with your eyes and feel with your hands, or in other words, visual and haptic information. When the operator and the slave are separated, the operator cannot directly acquire this information any more, so this information needs to be provided in another way. In the current teleoperation systems, there is often a pretty good representation of visual information from the slave side, using multiple cameras and even 3D images, which together provide a visual experience which sometimes even outperforms the information that the operator would normally receive when looking at the environment directly. However, designing haptic feedback in such a way that it resembles natural haptic feedback is still a big challenge. Because of technical limitations, it is still impossible to build haptic devices that can provide operators with haptic feedback which is similar to the feedback that they would have received when they had been performing the task with their own hands (Hayward, Astley, Cruz-Hernandez, Grant, & Robles-De-La-Torre, 2004; Srinivasan & Basdogan, 1997). Nonetheless, it might not be necessary to re-create all the natural feedback, because the haptic sense also has limitations. So, part of the answer to the challenge of designing applications more efficiently could be to take human perception into account (Hale & Stanney, 2004; Stanney, 1995; Vicentini & Botturi, 2010).

Apart from designing haptic feedback which resembles natural feedback as closely as possible, force feedback could also be used to provide the operator with extra information or to guide the operator towards a target position by adding extra forces. These are the concepts of haptic guidance or haptic shared control, in which the goal is that the human and machine perform a task together (Abbink, Mulder, & Boer, 2012). Usually, guidance forces are presented as an attractive force field around a target or as a tunnel which helps operators to stay on a desired trajectory. Haptic guidance mostly improves performance in terms of parameters like task completion time (Nitsch & Färber, 2013). However, studies also often report conflicts between human and machine when guidance forces are designed in this relatively simple way (e.g. De Jonge, Wildenbeest, Boessenkool, & Abbink, *In press*; Marayong & Okamura, 2004). Especially for tasks involving motor learning, it has been reported that using haptic guidance can even deteriorate task performance (Sigrist, Rauter, Riener, & Wolf, 2013). Apparently, designing guidance forces in this rather simple way is not always the optimal solution for the human user. Again, information on human perception could provide an answer to this. In the next section, a general introduction in haptic perception will be given.

1.2 Haptic perception

Haptic perception actually covers two perceptual subsystems: cutaneous perception, referring to the sense of touch, and kinesthetic perception, referring to the sense of body position and movement (Lederman & Klatzky, 2009; Loomis & Lederman, 1986). In cutaneous perception information is provided by two types of receptors, embedded in the skin: thermoreceptors and mechanoreceptors. Thermoreceptors are sensitive to temperature, while mechanoreceptors are sensitive to deformation caused by force or displacement. There are two types of thermoreceptors in the skin, which respond to warmth and cold. There are four types of mechanoreceptors in the skin, which all contribute to cutaneous perception: Meissner corpuscles, Merkel cell complexes, Ruffini endings and Pacini corpuscles. These four types of receptors can be categorized according to two properties: their receptive field size ('small' and 'large', also referred to as 'type I' and 'type II') and their adaptation rate ('slow' and 'fast', also referred to as 'SA' and 'FA') (Klatzky & Lederman, 2003). The receptive field size refers to the size of the skin surface from which a receptor obtains information, while the adaptation rate indicates how fast a receptor becomes insensitive to a stimulus when the stimulus does not change. By combining these different sensory properties, information about temporal and spatial characteristics of the touched object can be derived. For instance, fast adapting sensors are useful for detecting changes in the touched object, while the slow adapting types provide information about more stationary properties of the object.

Within the muscles and joints, there are three types of mechanoreceptors, which are the main receptors responsible for providing kinesthetic information: muscle spindles, Golgi tendon organs and joint receptors (Proske & Gandevia, 2012). Joint receptors provide information about joint angles based on the stretch and strain of the tissue inside the joints, while muscle spindles and Golgi tendon organs provide information about the state of the muscle and the resulting state of the tendon, from which arm position and movement can be inferred. Together, these receptors provide an image of body posture and movement.

Haptic perception can be investigated at many levels, ranging from recordings inside single neurons to experiments at a behavioural level. The approach in this thesis is a psychophysical one: by investigating the relation between the physical properties of a stimulus and the perception by a participant of that stimulus, regularities in these relations can be discovered, which allows for a general description of the relation between stimulus properties and human perception (Jones & Tan, 2013).

1.3 Psychophysics

In psychophysical research, the aim is to establish a relation between the properties of a stimulus and the perceptual experience of that stimulus (Jones & Tan, 2013). If this relation is known, predictions can be made about other stimuli than the tested ones, and these predictions can be tested again to validate the model. In psychophysical experiments, humans are usually asked to rate the property of a stimulus, either by rating the stimulus on its own (i.e. ‘how heavy is this cube?’) or by comparing two stimuli (i.e. ‘which of the two cubes is heavier?’). When using the former method, the main property that can be derived is stimulus intensity. A very common procedure for these types of experiments is free magnitude estimation. For instance, when cubes with different weights are used, participants are asked to rate the heaviness of each of the cubes. Usually, they are free to choose their own scale for this rating. These types of experiments can reveal the relationship between physical and perceived stimulus intensities.

When using the method of comparing two stimuli, usually one stimulus is the reference, which is kept constant throughout the experiment, while the other is the test, which varies in order to investigate the results of the variations of the property. The difference between the test and the reference stimulus determines the ease with which the participant can differentiate between the two stimuli. In the example with the two cubes, it is easy to imagine that if the reference is much lighter than the test, the participant will always answer that the test is the heavier one. If the reference is much heavier than the test, the participant will always answer that the reference is the heavier one. In between those extremes, there is a gradual transition from one answer to the other, which is called the psychometric curve. When assuming that the answers follow a normal Gaussian distribution, the psychometric curve can be described using a cumulative Gaussian distribution (Jones & Tan, 2013). An example of such a curve is shown in Figure 1.1.

From this curve, important perceptual properties can be inferred, which are: the Point of Subjective Equality (PSE, see Figure 1.1) and the discrimination threshold (‘DT’ in Figure 1.1). The PSE refers to the intensity of the test stimulus at which it is perceptually equal to the reference stimulus, which is the point where the response fraction is 50%. At this point, both stimuli feel equally heavy and thus the participant must guess. The bias (‘B’ in figure 1.1) is the difference between the PSE and the reference stimulus intensity. The larger the bias, the lower the perceptual accuracy.

When using a reference and a test cube that only differ in weight, while all the other properties are exactly the same, no bias is expected. However, when a property other than weight differs between the test and the reference stimulus, the effect of this property on weight perception can be assessed by looking at the bias. An example of a situation in which a bias can be expected, is when the reference cube is composed of a different material than the test cube and, as a consequence, has a larger volume, while weighing the

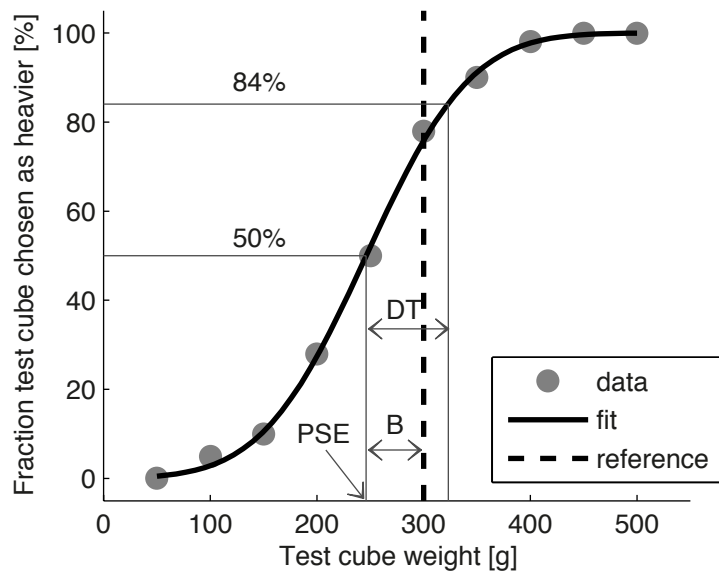


Figure 1.1: Example of a psychometric curve. For this hypothetical experiment, participants are asked to judge which of two presented cubes is heavier. On each trial, a reference stimulus with a constant weight (dashed line) and a test stimulus stimulus with varying weight (depicted on the horizontal axis) is presented. The reference stimulus is composed of another material than the test stimulus, which affects its perceived weight. For each test stimulus intensity, the fraction with which this stimulus is perceived as the heavier one is shown (gray dots). By fitting a psychometric curve to these data (thick black line), the PSE and the discrimination threshold (DT) can be inferred. The bias (B), which is the difference between the PSE and the reference stimulus, represents the perceptual accuracy, while the discrimination threshold represents the perceptual precision.

same. In this situation, the reference cube is probably perceived as being lighter than the test cube because of the size-weight illusion (Lederman & Jones, 2011). The size of the illusory effect can thus be inferred from the size of the bias. Biases between different senses are also frequently observed, such as the visuo-haptic bias: when moving your unseen hand to a visual target, you usually do not end up at the physical location of the visual target, so there is a difference between the physical and the perceived target location (Soechting & Flanders, 1989). In Chapter 8, such visuo-haptic biases are investigated.

The discrimination threshold describes the difference in stimulus intensity that is needed to reliably determine that the stimuli are different. In this thesis, a response fraction of 84% is used as the discrimination threshold. When a bias is present, the discrimination threshold is defined as the difference between the test stimulus intensity corresponding to a 84% response fraction and the Point of Subjective Equality, as can be seen in Figure 1.1. For higher discrimination thresholds, the perceptual precision is lower and the psychometric curve is flatter. The discrimination threshold is related to the perceptual noise. If our receptors and perceptual processing were noiseless, the discrimination

threshold would be very small, since tiny differences in stimulus intensity would be noticeable in that situation. This is usually not true, so therefore, the discrimination threshold is an interesting parameter. The discrimination threshold is also commonly expressed as a fraction of the reference stimulus intensity, which is called the Weber fraction. Weber's law states that the ratio between the discrimination threshold and the reference stimulus intensity is constant (Weber, 1978/1834). If the ratio between the two stays constant, this means that the absolute discrimination threshold increases with stimulus intensity. Although this law has proven to be wrong for some stimulus properties (such as the perception of symmetry (Van der Helm, 2010)), it generally holds for most medium-sized stimulus intensities. However, for small stimulus intensities a floor effect on the absolute discrimination thresholds is often observed, leading to an increase in Weber fractions for these small intensities (Durlach et al., 1989; Stevens & Stone, 1959; Tan, Pang, & Durlach, 1992). The discrimination threshold can be influenced in many ways. For instance, when the perception is restricted to be passive, which means that the stimulus is applied to the participant's hand, without him/her performing any active movements, the discrimination threshold is usually higher than when the participant is allowed to move freely and thus to perceive the stimulus actively (Symmons, Richardson, & Wuillemin, 2004).

1.4 Thesis outline

In this thesis, the precision and accuracy of haptic perception of several properties is investigated by determining biases and discrimination thresholds in psychophysical experiments. This thesis can be divided into 3 parts, which together cover different aspects of haptic perception and move from fundamental to more applied topics. The topics of the parts are: static haptic perception, dynamic haptic perception, and implications of haptic biases for haptic devices.

The first part consists of 3 chapters, Chapters 2, 3, and 4, which are all concerned with haptic perception under static circumstances, so stimuli are applied to the stationary hand of a participant. A logical question in this context is: how does a participant perceive that someone is pulling or pushing his/her hand? In all 3 chapters, the task for the participant was to perceive forces which were exerted on his/her hand, while (s)he had to keep his/her hand in the same position. In Chapter 2, a study on the effect of force direction on force perception in 2D is presented. In this chapter, biases in the perception of force direction and force magnitude were studied. These experiments show direction-dependent biases in force magnitude perception which were consistent across participants, while biases in force direction perception were also direction-dependent, but much more variable across participants. To further investigate the variable biases in force direction perception, the study in Chapter 3 was designed, in which the nature and

consistency of these direction-dependent patterns were examined. By studying a small group of participants at consecutive moments in time, the consistency of the biases within participants over time was investigated. By studying a large group of participants during one session, the consistency of the patterns across participants was investigated. Chapter 4 describes another follow-up study on Chapter 2, in which the investigation of biases in force magnitude perception was extended to a 3D situation. Moreover, since the patterns were very consistent across participants, a hypothesis to explain the nature of the biases was tested. This hypothesis was based on the notion that biomechanical parameters of the arm also show a direction-dependency, which is caused by the anatomy of the muscles, tendons, bones, and other tissues. The direction-dependency of biomechanical parameters of the arm seemed to align fairly well with the direction-dependency of the perceptual biases found in Chapter 2. To test this hypothesis, these biomechanical parameters of the arm were measured in Chapter 4 using system identification techniques. By also measuring the perceptual biases in force magnitude perception in this study, they could be compared directly to the measured biomechanical parameters to test the hypothesis that the latter were responsible for the biases in force magnitude perception.

The second part consists of 2 chapters, Chapters 5 and 6, which describe parameters that become important in dynamical situations, so when humans start to move their arm. Important aspects of movement are: the perception of one's own movements and the interaction with objects using movement. Chapter 5 is focussed on the perception of arm movement, by studying discrimination thresholds for movement distance for various types of arm movements. The research in this chapter tests if discrimination thresholds are affected by movement distance, movement direction, and stimulus type. Furthermore, a passive condition, in which a haptic device moved the participant's arm, was compared to an active condition, in which the device was moved by the participant. Chapter 6 revolves around the interaction with objects when moving. In particular, the perception of object hardness was investigated. It is already known that stiffness is very important in hardness perception (Bergmann Tiest & Kappers, 2014), but this chapter focusses on another object property, which is damping. This is also interesting for teleoperation applications. Teleoperation systems usually involve a delay between sending information from master to slave and back again, which can cause instabilities in the system. To avoid this, damping is often injected in delayed teleoperation systems. In this chapter, the effect of adding damping on the biases in the operator's perception of the hardness of objects within that system is investigated. Several levels of damping and object stiffness were combined in order to be able to construct an overview of the relation between stiffness, damping and perceived hardness.

The third part consists of 2 chapters, Chapters 7 and 8, which are more directly related to designing haptic guidance for teleoperation applications. Nonetheless, they also

answer questions that are interesting from a fundamental perspective, since they provide knowledge on the integration of sensory information. In Chapter 7, the integration of position and force information during the perception of force fields is described. Both the biases and the variability (which is related to the discrimination threshold) of the data were investigated. Two hypotheses were tested, which were both described in a mathematical model and thus could both be used to predict biases and variability. By comparing the experimental data with the model predictions, the validity of the hypotheses could be tested. In Chapter 8, the well-known paradigm of visuo-haptic biases (Soechting & Flanders, 1989) was used to test the use of correcting for user-specific perceptual biases in the design of haptic guidance. It has already been shown that correcting the mapping between operator and slave movements, by using parameters that are consistent across participants, increases user performance (Pierce & Kuchenbecker, 2012). However, the sizes of perceptual biases often differ between participants, and several types of biases are even completely user-specific (such as the biases in perception of force direction, which are described in the first part). The study in this chapter describes a comparison between a task in which physically correct haptic guidance was presented and one in which the haptic guidance was adjusted to the user-specific biases. Both the biases and the variability of the data were investigated.

Together, the three parts provide knowledge on fundamental parameters of haptic perception that can be important in the design of haptic devices. In the General Discussion chapter (Chapter 9), the implications of these findings for fundamental research and for haptic applications will be discussed.