General introduction
Exploratory movements in haptic perception

This thesis is about haptic perception, which is the formal synonym for ‘active touch’. The haptic sensory modality grants us our ability to feel the properties of objects in our surroundings. It comprises tactile sensory information as well as proprioceptive sensory information (Loomis and Lederman 1986). The term ‘active touch’ clearly indicates that active exploration – holding an object, stroking it, pressing it, or moving it around in your hand – is a crucial element of haptic perception. The importance of exploration is underscored by studies showing that different perceptual tasks elicit different kinds of exploratory movements (Lederman and Klatzky 1987; Riley et al. 2002), and that altering the characteristics of the exploration can influence the perceptual estimates (Drewing and Kaim 2009; Kaim and Drewing 2010). The work presented in this thesis examines the relationship between exploratory movements and haptic perception in detail, thereby addressing the question: how does the ‘active’ affect our ‘active touch’?

Before going deeper into haptic perception, I first would like to take a step back and address perception in general. What is perception? From a philosophical perspective one could say that perception is the only way we have to obtain knowledge about the world. It is the interface between physical reality and our subjective experience of a reality. Perception is unmistakably mediated by our sensory organs, which sample information from the surrounding world and convey sensory signals via our spinal cord to our central nervous system. There are several theoretical perspectives on perception. One prominent view – the one that I will adhere to in this thesis – is that the sensory signals provide imperfect sensory information because the sensory organs are prone to the two major shortcomings that are inherent to any measurement instrument. First, measurement instruments have a limited precision, which is reflected in random variability. For example, if you measure your body weight several times in a row, the scale will return a series of slightly different values. Second, measurement instruments have a limited accuracy, which is reflected in a systematic error (i.e., a bias). For example, if you measure your body weight several times in a row using two different scales, the average values returned by these scales may differ systematically. This indicates that at least one of them has a bias. Thus, our perceptual system has to cope with sensory information
that has limited precision (i.e., random variability) and that may contain biases (i.e., systematic errors).

The work presented in this thesis addresses the influence of exploratory movements on both precision and biases in haptic perception. First, I examine the influence of exploratory movements on the precision by which one can perceive the properties of a handheld rod. Second, I examine the influence of exploratory movements on the biases in the perceived length of a line that is traced with the hand. In the following I will introduce these two lines of research in more detail.

**Exploratory movements and haptic precision**

As indicated above, there are different theoretical views on perception. In the paragraph above, I explained that the brain has to deal with the shortcomings of sensory information when processing it into a perceptual estimate. The view that perception is an inferential process – because the sensory information is limited – dates back to H. von Helmholtz (von Helmholtz 1867; see Rock 1997) and can be referred to as the *constructivist* view (Norman 2002). A contrasting view is that sensory information is rich and complete, such that no processing is needed. This *ecological* view dates back to J.J. Gibson and it proposes that perception is merely the ‘detection’ or ‘pickup’ of information, a concept that is known as ‘direct perception’ (Gibson 1966; Michaels and Carello 1981).

The central question in the constructivist view is how the brain processes sensory information into a percept. Over the last two decades, major strides have been made in our understanding of how the brain deals with the inherent shortcomings (i.e., limited precision and biases) of sensory information, in particular when multiple information sources are simultaneously available. It was found that basic mathematical models adequately describe how a human observer integrates multiple sources of information (i.e., perceptual cues) into one stable perceptual estimate. This integration process boils down to a weighted average of the sensory cues whereby each cue’s weight is determined by its precision – the more precise the cue, the higher its weighting (e.g., van Beers et al. 1999; Ernst and Banks 2002). Such sensory integration can be considered beneficial for two reasons. First, it solves the problem of potential discrepancies between cues that may occur if different cues have a different bias. The bias in the integrated perceptual estimate will lie in-between the
separate biases. Second, the precision of the final perceptual estimate is better than that of the individual cues. Given the information content and the precision of the individual cues there is one combined estimate for which the precision is highest. This maximum likelihood estimate (MLE) is considered the ‘optimal’ perceptual estimate. Such optimal sensory integration has been observed within sensory modalities (e.g., Jacobs 1999; Drewing and Ernst 2006) but also across different senses (e.g., Ghahramani et al. 1997; van Beers et al. 1999; Ernst and Banks 2002; Alais and Burr 2004).

The central tenet of the ecological view is that perception is a direct process that does not involve operations by the brain. Unequivocal information is assumed to be available in the environment (i.e., the physical world) and it only needs to be picked up by the perceiver. This pick up of information is possible because the environment provides higher order invariants or ‘specifying variables’: perceptual cues that relate one-to-one to the to-be-perceived environmental properties. A well-known example is the inverse of the relative rate of optical dilatation of an object approaching the point of observation (referred to as ‘tau’), which specifies the remaining time-to-contact in interception tasks if the object approaches at a constant velocity (Lee 1976; Savelsbergh et al. 1991). The ecological approach ignores the limited precision and potential biases of the sensory information – these sensory limitations are brushed aside by the concept of higher-order specifying variables. In the haptic modality, the ecological approach had been used to study the ability that people have to feel the geometrical properties (e.g., length and shape) of unseen objects that they hold and move with their hand. This form of haptic perception has been referred to as ‘dynamic touch’ (e.g., Turvey 1996). The crucial question in ecological psychology is which higher-order specifying variables are used for the perceptual judgments. In dynamic touch, this question has been addressed in numerous studies and for numerous perceptual tasks, including the perception of rod length (for an overview, see Kingma et al. 2002).

Previous studies on haptic rod length perception have shown that the length estimates for a single rod can be very diverse when different kinds of movements are used to explore the rod (Kingma et al. 2004; van de Langenberg et al. 2006; Harrison et al. 2011). Van de Langenberg et al. (2006) showed that very distinct length judgments were made when the rod was held still at a horizontal orientation or a
downward vertical orientation (Exp. 1). Moreover, very distinct length judgments were made when the rod was wielded around a horizontal orientation or a downward vertical orientation (Exp. 2 and 3). Lastly, very distinct length judgments were made for fast and for slow downward wielding (Exp. 4). From the viewpoint of ecological psychology, these observations are difficult to explain. After all, as long as the length of the rod has not changed, the physical information – and thus the specifying variable – has not changed either. So what causes the perceptual estimates to change? The observations suggest that participants used multiple sources of sensory information. Moreover, the observations suggest that exploratory movements affected either which sensory information was used in the length estimate, or the degree in which multiple sources of information were used in the estimate. The former possibility – participants switched in the information that they picked up – challenges the ecological view with the question: how does the environment prescribe the switch point? The latter possibility – participants used multiple sources of information to a varying degree – challenges the ecological view with the question: how does the environment prescribe the degree to which information was used and how is the information united in a single percept? What these questions illustrate is that it is difficult to explain the effect of exploration style on length estimates without ascribing information processing capacities to the brain.

Whereas the above findings in rod length perception – different exploratory conditions lead to different rod length estimates – appear hard to reconcile with the viewpoint of ecological psychology, they match well with the constructivist’s view and in particular with the principles of multisensory integration. As argued in the preceding, multisensory integration amounts to a weighted averaging of sensory cues, with the precision of each cue determining its weighting. The observation that exploration affects rod length estimates gives rise to the hypothesis that exploration directly influences the length cues’ precision. The first part of this PhD thesis addresses this hypothesis.

**Outline part I**

In Chapter 2 I tested the hypothesis that rod length perception is based on a weighted combination of length cues, whereby the exploration forces determine the cues’ weights. We asked participants to explore the rods by wielding them with different
levels of force. The exact magnitude of these forces was subsequently derived from the recorded rod movements. We used rods whose mass distribution was carefully manipulated. There was one rod with a baseline value for mass \((m)\), the first moment of mass distribution \((M)\), and the first principal moment of inertia \((I_1)\). In addition to this baseline rod there was one rod with an increased \(m\), one rod with a decreased \(M\), and one rod with an increased \(I_1\). These independent variations of the rods’ inertial properties allowed us to assign differences in length judgment to specific inertial properties or combinations thereof. In our endeavor to model rod length perception as a weighted combination of length cues, we encountered two major questions: how do the inertial properties constitute length cues and what aspect of the exploratory movements determines the cues’ precision and thus their weighting?

From the quantitative model for rod length perception that we developed in Chapter 2, we obtained the hypothesis that exploration force is directly related to the precision of sensory information. In Chapter 3 we tested this hypothesis by focusing on one specific inertial rod property – moment of inertia – in a two-dimensional situation. We used one rod that was fixed on an axis in its center of mass and whose moment of inertia could be adjusted from trial to trial. Participants were instructed to rotate the rod with different levels of force and to judge its moment of inertia (i.e., resistance against angular acceleration or ‘angular mass’). From these judgments we determined the participants’ perceptual precision. The prevailing view on perceptual precision is that it is a fixed proportion (i.e., the Weber fraction) of the sensory stimulus’ magnitude. In this study I challenged this idea of a constant Weber fraction by examining whether exploration affects perceptual precision. The major question was: what is the quantitative relationship between exploration force and perceptual precision?

Finally, Chapter 4 presents a methodological study. We hypothesized that the experimental apparatus that is conventionally used to measure rod length perception reduces the precision of the recorded rod length judgments. This precision is determined by the variability that is inherent to the haptic task as well as the variability of the apparatus. When studying sensory integration it can be very useful to introduce artificial biases to the sensory information in order to create conflicting cues (e.g., Ernst and Banks 2002; Gepshtein et al. 2005). The magnitude of such cue conflicts is limited however, in order for the brain to still integrate the information
As a result, one may be looking for subtle changes in perceptual estimates (i.e., length estimates in our case). Additional variability is very disadvantageous in such a paradigm because it obscures the subtle effect of the experimental manipulations and hence reduces the experiment’s statistical power. In this study we aimed to develop a virtual reality apparatus that adds minimal variability to the rod length estimates. To test the apparatus we examined whether it provides more precise recordings of rod length estimates than the conventional apparatus.

**Exploratory movements and haptic biases**

As indicated at the beginning of this introductory chapter, the second part of my thesis is about the influence of exploratory movements on biases (i.e., systematic errors) in haptic perception. In particular, this second part of the thesis concerns a haptic bias that has been known in the literature since the 1950s (Reid 1954) but which is still poorly understood. When one traces the outline of an unseen L-figure in the horizontal plane, the length of the radial segment (i.e., towards and away from the body) is overestimated relative to the length of the tangential segment (i.e., parallel to the body) (e.g., Davidon and Cheng 1964; Cheng 1968). This bias is referred to as the radial-tangential illusion. The effect is rather strong: for a shape to feel square, it must be a rectangle with a tangential length that is about 20% larger than the radial length (McFarland and Soechting 2007). Interestingly, the radial-tangential illusion occurs when the stimulus is explored with the whole arm (i.e., movement of both upper arm and forearm), but not when stimulus exploration involves movements of the forearm and hand only (Heller et al. 1997). This illustrates that the illusion results from a bias in the perceived extent of the exploratory arm movements rather than from the physical characteristics of the L-shaped stimulus. In the second part of my thesis I propose a new hypothesis about which specific aspect of the exploratory movement causes the biased perception of arm-movement extent.

**Outline part II**

In Chapter 5 we briefly review the main characteristics of the radial-tangential illusion. Based on these characteristics we propose a new hypothesis regarding the origin of this illusion, namely that the overestimation of arm-movement extent is
positively related to the difference in torque needed to counteract gravity between the start and end of the movement (ΔTorque). In order to test whether this ΔTorque hypothesis is plausible, we built a simplistic model of a two-segment arm to simulate three different experiments as reported in the literature. Our main question was: is the ΔTorque model able to explain the effect of different experimental manipulations (i.e., movement extent and exact movement direction) on the strength of the radial-tangential illusion?

In Chapter 6 we tested the ΔTorque hypothesis experimentally by manipulating the magnitude of ΔTorque. Participants were asked to trace the two segments of an L-figure in the horizontal plane (i.e., one radial segment and one tangential segment) and to report which of the two segments they felt was longer. We varied the length of the radial segment from trial to trial, and thus we could determine the radial length at which the radial and tangential segments were judged to be equally long. This measure quantifies the strength of the radial-tangential illusion. We increased the magnitude of ΔTorque by adding mass (0.5 kg) to the participants’ wrist. The ΔTorque hypothesis predicts a stronger illusion in this condition than in a baseline condition without additional mass. In a control condition we added mass to the participants’ elbow, thus increasing the overall level of gravitational torque without affecting ΔTorque. The ΔTorque hypothesis predicts no difference in the illusion’s strength between this condition and the baseline condition without additional mass. By testing these predictions we examined the question: are biases in perceived arm-movement extent caused by the changing magnitude of the gravity-counteracting muscular torque during the movement?

In summary

In this thesis I examine the role of exploratory movements on haptic perception. In the first part I address the influence of exploratory movements on the precision of haptic rod length perception (chapters 2-4). In the second part I address the influence of exploratory movement on the biases in the perceived extent of a tangible line segment (chapters 5-6). Finally, in Chapter 7 the results and implications of these studies are discussed.