General introduction
Chapter 1
Where is my hand? Probably you don’t think about this question too often. However, knowledge about the position of your hand is essential during your daily interaction with all kinds of objects. So how do you know where your hand is? The first answer that comes to mind is that you can see it. However, vision is not the only factor that is important for knowing where your hand is. For example, you can touch your nose with your eyes closed and you can clap your hands behind your back. Both cases do not involve vision. A second important factor to know the position of your hand is proprioception: the feeling of where your hand is.

In this thesis I present various experiments that we performed to get more insight in the mechanisms of proprioception and in the different factors that play a role in proprioceptive position sense of the hand. Some of the experiments are fundamental and designed to gain knowledge about the proprioceptive systems. Other experiments are designed to be translated to applications in the domain of haptic tele-operation systems.

**Proprioceptive position sense**

Proprioception is based on two types of information that humans can use to know where their limbs are: afferent and efferent information (e.g., McCloskey, 1978; Gandevia et al., 2006). Afferent information is sensory information derived from cutaneous, muscle and joint receptors. All these receptors deliver information about the posture of the arm and hand relative to the body and send this to the brain. Efferent information, or the efference copy, is an internal copy of the motor signal that is sent to the motor system to move the arm or hand. Efferent information therefore provides an estimate of the intended posture in advance, while afferent information provides feedback of the achieved posture. The combination of the inputs of all sources of information results in an effective and reliable proprioceptive position sense.

One could question why so many input sources are necessary. Probably, the reason that so many different types of information contribute to human judgments of proprioceptive position sense is that none of them alone is very reliable. For example, several studies have shown that without afferent information, when only efferent information is available due to anesthesia or lesions, you cannot correct for errors in the execution of the movement, e.g. unexpected forces or obstacles during the movement (e.g., Polit & Bizzi, 1978; Smith et al., 2009). On the other hand, basing your percept purely on afferent information is also tricky, because afferent information is also not perfect. For
example, the relation between the firing rate of various receptors and the position of the arm is not a simple one-to-one mapping, but depends on the amount of exerted force (Matthews, 1964; Kistemaker & Rozendaal, 2011).

In the absence of one precise and completely reliable source of information, it makes sense to combine all possible information, weighted according to their precision (e.g. Young et al., 1993; Van Beers et al., 1996, 1999; Ernst & Banks, 2002) and possibly also accuracy (Van Beers et al., 2011). Manipulating one of the sources of information and seeing whether and how this affects the overall percept can give insights in the weighting of the information.

The first part of this thesis (chapters 2-4) is based on this approach. We use force field manipulations in chapter 2 and 3 and skin stretch manipulations in chapter 4. Force fields affect the afferent information of the muscle spindles and probably also the efference copy, while skin stretch manipulates mainly the cutaneous information (afferent).

**Tele-operation**

Besides fundamental reasons to investigate proprioception, there are also technical interests to know how one knows where one's hand is, e.g. in tele-operation. Tele-operation is acting at a distance; acting at a place where you are not. Tele-operation systems are currently being used and developed in many different technical areas, e.g. complex medical surgery, deep-sea mining, and for maintenance in nuclear power plants and space stations. Instead of interacting directly with the environment, the operator works with a robotic interface, called the master device, which communicates with another robotic device, the slave, which is in the environment. In this way dangerous tasks or tasks at places that are impossible to reach for humans, can be done from a (safe) distance.

To perform well and get a good percept of what is happening while interacting with the environment, the operator needs sensory feedback. So far, this feedback is mainly visual. Cameras show the tool of the slave and the environment, and the operator works with these ‘remote eyes’. A next step in the development of tele-operation systems would be to provide haptic feedback; to give the operator ‘remote hands’. To develop remote haptic interaction efficiently and realistically, it is important to know how haptic interaction with objects works when handling them directly. Ideally one would make a perfect transparent representation, where the forces on the operator are an exact copy of the interactive forces between the slave robot and its
environment, to make the interaction as similar as possible to direct interaction (e.g. Boessenkool et al., 2013). However, this is very unlikely to be realized due to several technical aspects, such as delays in the system and the need of perfect sensors to be able to provide perfect feedback. An alternative approach to improve tele-operation systems is to offer haptic shared control.

**Haptic shared control**

Haptic shared control is a concept in the development of tele-operation and haptic devices in which the device provides additional information about the interaction between the device and the environment, e.g. in the form of haptic guidance (e.g. Steele & Gillespie, 2001; Abbink et al., 2012). This additional information is designed to guide and help the operator, but the operator can always take over and ignore the guidance. The basic idea of haptic shared control is that both the human operator and the haptic controller (a computer) make a ‘plan’ about how to perform the task. The haptic controller would communicate his plan to the operator by forces, i.e. haptic guidance. In this way the transparency of the haptic system does not have to be perfect, because the haptic guidance could compensate for the lack of direct feedback information (Boessenkool et al., 2013). In the automotive industry haptic shared control has been developed to optimize the gas pedal of the car and to diminish effort of getting the right steering angle to stay in the lane (e.g. Steele & Gillespie, 2001; Mulder et al., 2008a; Mulder et al., 2008b).

In tele-operation systems, haptic shared control with haptic guidance is very promising, however, so far it is unknown whether haptic guidance affects the perception of the (actions in the) environment. For example, does one know correctly where one’s hand is when moving in a force field? And can forces be used for guiding purposes or do they interfere with haptic perception. To get more insight in how haptic shared control and haptic guidance should be designed to be most effective, we evaluated the fundamental results in this thesis with respect to implications for these systems.

**Sensory matching tasks**

The typical methods that I used in this thesis are sensory matching tasks. In a sensory matching task, human subjects have to match the positions of two items, e.g. matching the unseen hand (proprioceptive position sense) to a visual target (visual position sense). This is not as easy as it sounds, because
the position information of both items is not presented in the same way. In both percepts of the position, and in the transformation of the position information between the two modalities, errors might occur. These errors lead to sensory mismatches, e.g. visuo-haptic matching errors (the matching errors between a visual and an haptic item) or haptic-haptic matching errors (the matching errors between the two hands). These matching errors are not just random noise, but systematic idiosyncratic, i.e. subject-dependent, biases.

In the first part of this thesis (chapters 2-4) we used the visuo-haptic matching error to see whether a haptic manipulation affects the proprioceptive position sense. This method is the haptic analogue of studies in which the visuo-haptic matching error was used to investigate visual manipulations (e.g. Sousa et al., 2010). We compared the visuo-haptic matching errors with and without manipulations. Later experiments were designed to get more insight in the sensory matching errors themselves (chapters 5-7), while in chapter 8 we used the findings about sensory matching errors to improve performance in a task with haptic shared control.

Overview of this thesis

In the first three chapters of this thesis, I will present experiments that are aimed at identifying essential factors in proprioceptive position sense. To do this we use different methods to manipulate the proprioceptive systems: force fields and skin stretch. In chapter 2, the influence of horizontal external force fields on the proprioception is investigated. The force fields are irrelevant to the movement and do not provide information about the task, but because of the different force fields both efference copy of the motor commands (efferent) and the feedback of the muscle spindles (afferent) are affected by the manipulation.

Because it has been suggested that vertical forces, or more specifically the torques around the shoulder, play an important role in judging the position of the hand (Debats et al., 2010), we study the effects of vertical force fields on position sense and hand movements in chapter 3.

In chapter 4, we study a different manipulation of the proprioceptive system, skin stretch, to manipulate the input of the afferent cutaneous information. From previous studies is known that cutaneous manipulations influence proprioceptive position sense when subjects had to judge or match the posture of their limbs (Edin & Abbs, 1991; Edin & Johansson, 1995; Collins & Prochazka, 1996; Collins et al., 2000; Weerakkody et al., 2007). In this
chapter we explore the effect of non-invasive manipulation of cutaneous information in active reaching. In this manipulation both proprioception and the efference copy of the motor command are expected to play a role. The skin stretch manipulations were done with a relatively new method using elastic sports tape.

In the next three chapters I focus on the characteristics of the sensory matching errors themselves. Why do these matching errors exist and how consistent are they? In the first chapters, we found similar idiosyncratic visuo-haptic matching errors on different blocks and sessions within each experiment. These results suggest that visuo-haptic matching errors are quite consistent across time and sessions. However, none of these studies were actually designed to test how consistent the visuo-haptic matching errors are across time or session, and they did not really attempt to quantify the amount of consistency. Therefore we started to develop a method to quantify the consistency between the matching errors in different sessions in chapter 5. This method is further developed in chapter 6.

In chapter 5, we explore the consistency of the matching errors over different reaching methods used in literature; are visuo-haptic matching errors the same when reaching with the index finger or with the fist holding the handle of a hand-held haptic device? And how about the precision of these different ways of reaching? Intuitively one might expect that we would make more precise movements when reaching for a visual target with our index finger than when reaching with a hand-held device in a power grip. In this chapter we test whether this intuition was reflected in the precision of visuo-haptic matching errors.

In chapter 6, we present a new method to quantify the consistency between sensory matching tasks. We used this method to quantify the consistency of visuo-haptic and haptic-haptic matching errors over time intervals varying from 5 minutes up to almost two months.

In chapter 7, we investigate the relevance of the posture and the hand used in sensory matching tasks. Are haptic-haptic matching errors caused by differences between the postures of the hands or because of the use of two hands? Because we show differences in matching errors over hands and postures in this experiment, we present a second experiment in which we examine whether really the hand and posture are critical, rather than some other aspect of the differences between the tasks. Therefore, we use tasks that are designed based on the same matching configuration (both in terms of
visual locations and of the arm and its posture), but involved different actions to reach this configuration. For example, is moving the hand to a visual dot the same as moving a visual dot to the hand?

The experiments in the last two chapters of this thesis are more applied. In chapter 8 we explore whether performance could be improved by individualizing haptic guidance. In this chapter we use the fact that sensory matching errors are very consistent (as was shown in chapter 6) and we implement this to optimize shared control in haptic tele-operation systems. First, we measure the personal visuo-haptic matching errors. Then, guidance will be provided either towards the physical target positions or towards the idiosyncratic matched positions (the positions the subject would reach for according to their idiosyncratic matching errors) without the subject knowing. We compare whether user performance improves when the haptic guidance is individualized.

Besides spatial factors that influence haptic perception in tele-operation systems, also temporal factors might influence the quality of the haptic percept. From research on time perception and adaptation to delays in various sensory modalities, we know that delays can change perceived stimulus characteristics (e.g. Bloch, 1885; Keetels & Vroomen, 2012). In haptic systems, there are delays between the applied force and the corresponding movement, which might affect the percept of the operator. In chapter 9, we study the effect of delays on the perception of mass in an admittance-controlled haptic device.

Finally, the thesis ends with a general discussion in chapter 10, consisting of an overview of the main results with their implications and recommendations for both fundamental research on proprioception, and the design of haptic shared control systems.