Chapter 9

General discussion

This thesis examined various aspects of haptic search. It consisted of three parts. In the first part, the saliency of movability and compliance were investigated. In the second part, the combination of texture and shape was evaluated in a haptic search task. Finally, the exploration movements that are used in haptic search were examined. In this last chapter, I will discuss the results and implications of the studies that were described in each part.

Salient features make a search easy

When an object contains a salient feature, it is easily detected among other objects that do not possess that feature. Some of these known salient properties in haptics are roughness, edges (Lederman & Klatzky, 1997; Plaisier et al., 2008, 2009b) and temperature (Plaisier & Kappers, 2010). The saliency of roughness and edges was further supported in Chapter 4. The search for a cube among spheres was faster than the search for a sphere among cubes. Similarly, the search for a rough sphere among smooth spheres was faster than the reversed situation. Interestingly, this search asymmetry for roughness compared to smoothness was found when the items were grasped. Previously, the saliency of roughness was demonstrated only in a 2D search task (Plaisier et al., 2008).

Furthermore, in Chapter 2, it was shown that movability can also be considered a haptic salient feature. Further measurements indicated that the vibrations caused by the mechanical interactions between the ball and its casing might be responsible for the pop-out of movability. Another property that was examined for its salience was compliance. Hardness and softness were already investigated in a static search by Lederman and Klatzky (1997), but in Chapter 3 this saliency was also confirmed in more active tasks. This was both for the case where items were felt in the hand and when they were pressed on a display. For a hard target among soft objects, it did not matter whether the objects were held in the hand or could be pressed on a display. In both cases the hard target popped out and flat search slopes were found. For a soft target among hard distractors, an efficient search was found when the items were held in the hand, but not when they were placed on a display. This indicated that the saliency of a property not only depends on its context, but also on the way it can be explored. In this case, the exploration of the soft sphere was restricted by the hard distractors.

With the addition of movability, hardness and softness, a substantial list of haptic salient features are identified. This demonstrates that haptic perception can be fast and efficient. Salient features are extracted rapidly from the environment. Therefore, they might influence the perception of an object more than other properties in the first phases of contact. It is possible that these properties are important for the fast recognition of objects, because they are perceived so early and efficiently. Of course, many more possible salient features can be investigated. For instance, vibration, slipperiness or weight might be candidates. These are properties that seem to be more suitable to be perceived with the haptic modality than other modalities, making them likely to be salient in haptic perception. From the study of Lederman and Klatzky (1997), where many properties were investigated, properties that are intensively coded (e.g. materials) seem to be processed more efficiently than spatial properties (e.g. orientations).

What determines whether a feature will be salient or not? First of all, the saliency of a property is relative to its context. Therefore, the saliency will depend on how much the target differs from the distractors (see also Duncan & Humphreys, 1989). In Chapter 3, this was shown for hardness and softness. When the difference between the target and the distractors was small, no pop-out effect was found. Other research has also found an influence of discrimination difficulty on the search slopes (Lederman & Klatzky, 1997; Plaisier et al., 2008).

However, the difference between target and distractors cannot be the only explanation. For instance, a rough and a smooth object are very easy to discriminate, but still only the rough object will pop out among the smooth ones and not the other way round. According to Treisman and Souther (1985), such search asymmetries can be explained because some visual features are so-called primitives and others not. They reason that the visual primitives have neural detectors, whereas other features do not. So, if one has to search for the presence of a visual primitive, only the neural activity for this feature has to be monitored. In the search for the absence of a primitive (i.e., the presence of a property on the other end of the dimension range), this is not possible. In this case, the signal-to-noise ratio will be low. With respect to feature detection, a similar explanation is proposed by Wolfe and colleagues (Wolfe et al., 1989; Wolfe, 1994), although they propose a larger role for top-down guidance. For features on both extremes of the dimension that are both salient, Treisman and Souther (1985) state that these features are substitutive. This means that the absence of one feature necessarily means the presence of another. In haptic perception, this might be the case for hardness and softness. In such cases, it is assumed that there is a detector for both features.

In the haptic domain, Lederman and Klatzky (1997) agree with a signal-to-noise explanation for their asymmetries in a tactile search task. The question remains whether actual haptic detectors exist and where they could be found. Possibly, a neural basis for these detectors might already be sought in the periphery. The activity of certain skin receptors might indicate the presence of a certain feature. These receptors are perhaps more sensitive to certain features than to others. Moreover, some properties might also 'share' a detector. For instance, the sharpness of an edge or a rough patch might be perceived by a similar receptor and cause both features to be salient. On the other hand, top-down control (e.g., the tuning of receptor activity) could certainly play a role as well. In fact, higher brain areas should also not be ruled out. A study of Downar, Crawley, Mikulis, and Davis (2002) showed that a common multimodal network was active in response to salient tactile, visual and auditory stimuli. However, here the salient feature was 'novelty' (as compared to familiar stimuli), which might be a more complex salient feature and thus require higher level processing.

Salient features make a search difficult

Salient features are detected quickly and can make a search for an object very efficient. In contrast, in Chapter 4 we saw that salient features can also disrupt performance. When all stimuli in the set contained an irrelevant salient property, the search was slower than when the stimuli did not contain that salient property. For instance, the search for a rough cube among smooth cubes was more difficult than the search for a rough sphere among smooth spheres. Even if a property is not relevant for the task, it still can influence the perception. This might also be explained by a difference in signal-to-noise ratio. The salient properties add a lot of noise to the scene, because they are easily perceived even though they are irrelevant. The effect of a salient disruption was only seen in tasks that previously showed an efficient search. Perhaps in the searches that were already difficult, there was already some noise, so an increase in noise did not have a large effect. These results can also be explained in terms of exploration strategies. With the addition of the salient feature, the efficient searches shifted from a parallel to a serial search whereas in the difficult searches the strategies where serial in both cases.

Nevertheless, this disrupting performance might also be property dependent. In Chapter 4, shape and texture were combined, where roughness and edges (in the cubes) were the salient features. It is possible that these features are (partly) detected with common receptors in the skin. Then, the activity in the receptors might be caused by an irrelevant feature, but also activity of the relevant property is expected in this receptor. In two properties that activate different receptors, less disruption might be possible. This question remains to be evaluated. However, the influence of various salient features on shape perception (Panday et al., 2012; Bergmann Tiest et al., 2012) suggest that these properties influence the perception not only by activation of a common receptor, but an influence on a higher neural level might also be expected.

When investigating the balance between cues and disruptions, roughness might be a more disruptive stimulus, whereas shape might be more beneficial (Chapter 4). The model that was made in Chapter 4 was in accordance with these results. The 'weights' that were calculated in the model revealed that the disruption weight was larger than the weight of the cue for roughness, whereas the reverse held for shape. Perhaps roughness is more disruptive than helpful in discriminating objects, whereas for shape it would be the opposite way. However, this can only be concluded for the stimuli that are used in that study. In addition, the stimuli had to be grasped in all conditions, which might not be an optimal exploration procedure for the roughness stimuli (Lederman & Klatzky, 1987). Whether these differences in cues and disruptions exist in other situations remains to be evaluated. Such analyses might be useful for designers of haptic devices. They could focus on minimising disruptive features and maximising beneficial cues.

Two properties can be integrated

In the perception of objects, the object generally contains multiple properties that distinguish it from others. As mentioned earlier, the detection of a target object gets easier when it differs more from the distractor objects. This can be accomplished by increasing the difference between the objects within the single discriminating feature, but also by introducing more properties that distinguish the target from the distractors. If two properties can enhance search performance compared to both searches with only a single property difference, we speak of integration of the two properties.

In Chapters 4 and 5, it was shown that texture and shape could be integrated in haptic search. Interestingly, this integration seems to be only possible, or at least most effective, if the two properties are not salient. This is compatible with findings of other (multimodal) integration studies, where weaker signals seem to achieve better integration results. This is called the law of inverse effectiveness (but see Holmes, 2007, for a critical note). With the combination of two salient properties, there might be a floor effect. The search is already so fast and efficient that there is not much room for improvement. If a salient and a non-salient property are combined, the salient property might be dominant, and the focus is only on the salient feature. This result was found in Chapter 4 in the search for one combination of a salient and non-salient cue, but not for another combination.

How this integration effect could be explained was investigated in Chapter 5. Instead of a coactivation of signals, where these might be somehow pooled or combined to enhance detection, it was found that the properties were processed independently in parallel. Furthermore, there was an advantage if the properties were located in the same object, compared to different objects. So, it seems that this parallel processing is not completely effective when the properties are located in different objects.

So far, feature detection in haptic search might be explained by similar models as in vision. It gets more complicated when the combination of more properties is considered. This is because an important difference between haptic and visual search is that in haptic perception the stimulus set can be explored in a dynamic way. When items are presented on a display, the search might not be so different from a visual display on a screen, but the search for objects in the hand, which can be manipulated and moved, is essentially different from a visual search. This poses a problem with common visual theories, where the features of different objects are represented on a 'map' (Treisman & Souther, 1985; Wolfe, 1994). In a dynamic haptic search where the items move as well, such a map would be difficult to form.

For the detection of the presence of a single feature, a map is not necessary, but in the combination of features to form objects, the representation and combination of maps becomes more difficult to apply to haptic search. In the studies in this thesis, the targets with two cues differed from all distractors in two properties. A more complicated situation arrises when a conjunction target is a unique combination, i.e., where half of the distractors share one property with the target and the other half another property. It is also in the explanation of searches for these conjunctions of features that visual theories differ most (e.g. Treisman & Gelade, 1980; Treisman & Sato, 1990; Wolfe et al., 1989; Wolfe, 1994; Duncan & Humphreys, 1989). In this thesis, I have not looked at conjunction searches. So, whether and how these visual models can be applied to haptic search remains to be investigated.

One perceptual explanation for the coactivation of properties can also be described in the combination of maps (Krummenacher et al., 2002). If two feature maps with each a high activity for one feature are merged, a much higher activity peak is created. This peak would then be detected more easily. Since the existence of spatial representations of maps in haptic search similar to vision is questionable, does this mean that coactivation is not possible in haptic perception in principle? Not necessarily so since other explanations for coactivation are that the features are pooled at the decision or response stage (Krummenacher et al., 2002). In addition, Chapter 5 also showed that the integration was more efficient if properties were located in a single object, which suggests that some representation of objects might still be formed.

In this thesis, I only focussed on the integration of texture and shape. Perhaps things might be different for other combinations. The level of integration and how the two properties are processed can differ between the combinations as well. One might imagine that properties that have compatible exploratory procedures (Lederman & Klatzky, 1987) would have a larger gain in search performance than properties that are more difficult to perceive at once.

Exploration movements are adjusted to the search

Finally, the saliency of the target also seems to have an effect on what kind of search strategies humans use. The most efficient strategy is chosen to be able to perform the task fast, but also accurate (Chapters 6 and 8).

What kind of strategies are seen, is also dependent on the set-up. Different movements are observed in a 2D set-up and a 3D set-up. In a 2D set-up, where the stimuli are placed on a display, sweeping movements over the display are seen. The kind of movements are comparable in a search for roughness and for movability. The study of Plaisier et al. (2008) seems to show similar movements as described in Chapter 6. Although different properties are to be searched for, the exploration strategies are adjusted to the saliency of the target in a similar way: in an easy search task, simple, short sweeps are performed and in a difficult search, detailed, complicated movements are seen.

The same results are found in a 3D task. Here, the movements are more grasping and manipulation motions of the items in the hand, but the explorations are adjusted to the saliency of the target. Chapter 8 showed that for both texture and shape searches, the exploration strategies were adjusted in a similar way. In an easy search, a simple grasp or short manipulation was found, whereas in a difficult search detailed and extensive manipulation and exploration movements were seen. In addition, the fingers were used more extensively to contact the target in difficult searches. In particular, the thumb was used often at the end of the trial, possibly to identify the target. So, both in 2D and 3D search tasks, a distinction between parallel and serial strategies can be made, dependent on the saliency of the target and much less on the specific property.

These differences in search strategies give an even clearer distinction between difficult and easy searches. The interpretation of a search slope value is difficult, because there is no strict boundary between serial and parallel search. In visual search, a continuous range of slope values has been found (Wolfe, 1998) and the same seems to be true for haptic searches. Also in the movements, a range of exploration movements can be seen. The possible strategies can vary from a single grasp to little manipulation to actual one-by-one exploration of the objects. When interpreting the search slopes, it seems that the values are generally higher in haptic searches compared to visual searches. However, the evaluation of the movement strategies clearly indicates search differences. It seems that for the interpretation of the slopes in haptic search, it is important to consider the manner of exploration as well. An easily observable measure is the dropping of items out of the hand. When this occurs, the items clearly cannot be perceived in a parallel manner.

The identification of 'typical' exploration patterns is helpful in the development and control of robotic devices. For the exploration of single objects, exploratory procedures have been described (Lederman & Klatzky, 1987) and even synergies have been determined (Thakur, Bastian, & Hsiao, 2008). Synergies are coordinated movements between the joints that simplify the immense possible range of motions. A specific movement may consist of a combination of different synergies. Perhaps different stereotyped movements or synergies may also be defined in haptic search tasks. In the perception of multiple objects, so many movements are possible to explore the objects. Little is known about how multiple objects are explored simultaneously. However, humans seem to be able to select the most efficient way for detecting the required information. The hand model in Chapter 7 provides a tool to further investigate how objects are explored and which parts of the hands are used. This information could be useful in the development of sensors in haptic feedback applications. The advantage of the model is that it requires few sensors and the cutaneous perception is not restricted by the covering of the skin.

Conclusion

We have seen that specific properties can be perceived fast and efficient in haptic perception. Whether a feature is salient with respect to its context seems to have a large influence on the perception of a scene and how this is explored. In addition, in the handling of multiple objects, humans can efficiently detect the required information and integrate multiple cues.

So, how can you improve on finding your phone in your bag? Perhaps you could make it more distinctive from the other stuff in your bag by adding a salient feature (e.g., a textured cover). It would be even better to make sure the phone differs from the other objects in multiple properties and that those do not possess very salient features. Then, you could perform a quick, parallel search to easily detect the phone.