# Chapter 5

# Parallel processing of shape and texture in haptic search


**Abstract**

*In a haptic search task, one has to determine the presence of a target among distractors. It has been shown that if the target differs from the distractors in two properties, shape and texture, performance is better than in both single-property conditions [Van Polanen, V., Bergmann Tiest, W.M., Kappers, A.M.L., 2013. Integration and Disruption Effects of Shape and Texture in Haptic Search. PLoS ONE 8, e70255]. The search for a smooth sphere among rough cubical distractors was faster than both the searches for a rough sphere (shape information only) and for a smooth cube (texture information only). This effect was replicated in this study as a baseline. The main focus here was to further investigate the nature of this integration. It was shown that performance is better when the two properties are combined in a single target (smooth sphere), than when located in two separate targets (rough sphere and smooth cube) that are simultaneously present. A race model that assumes independent parallel processing of the two properties could explain the enhanced performance with two properties, but this could only take place effectively when the two properties were located in a single target.*



*Vonne van Polanen, Wouter M. Bergmann Tiest, & Astrid M. L. Kappers (in press). Parallel Processing of Shape and Texture in Haptic Search. Acta Psychologica.*

## 5.1 Introduction

When multiple properties distinguish one object from another, the objects can be more easily discriminated than with just a single distinguishing factor. For example, in haptic perception, when turning off the alarm clock in the morning when it is still dark, one has to locate the button on the alarm clock by touch. This button can be located, because it differs in shape from the flat surface of the alarm clock. With more property differences, e.g., by giving the button a ribbed surface, the task gets easier. For this to work, the properties must be integrated. It has been shown that various sources of information can be combined within several modalities, like vision, audition and haptics, and across modalities (e.g. Ernst & Bülthoff, 2004). In haptic perception, effective integration has been found, for example, in studies investigating shape discrimination (e.g. Drewing & Kaim, 2009; Voisin et al., 2002). These studies are examples of situations where objects differ in a single property, but multiple cues can be perceived to define that property. For instance, when discriminating shape, one can use proprioceptive and cutaneous cues. Other studies have also indicated that different object properties can be integrated to improve object recognition (Klatzky et al., 1989).



Recently, we have shown that properties can also be integrated in a haptic search task (Van Polanen, Bergmann Tiest, & Kappers, 2013). In a search task, one has to determine the presence of a target among certain distractor items. Participants have to do this as fast and as accurately as possible and usually reaction times and/or the number of correct answers are measured. If a target can be perceived almost immediately among the distractors, this is called the pop-out effect (Treisman & Gelade, 1980; Treisman & Souther, 1985). The target then possesses a feature that is perceived automatically and pre-attentively, which can also be referred to as a salient feature. In an experiment, this can be measured by looking at the time the participant needs to determine the presence of a target: the reaction time. If a target pops out, the reaction times will not change with the number of items: both with a small and a large number, the target is spotted easily. The property is then searched for with a parallel strategy, where all items are perceived at once. This is in contrast to a serial strategy. In that case, the items are explored one at a time, which is a more time-consuming search. The reaction times will, therefore, increase with more items. In haptic search, the strategy that is used to determine target presence can also be observed by looking at the exploratory behaviour that is used. For instance, if the stimuli only need to be grasped in the hand for a short time, this can be considered a parallel exploratory strategy. On the other hand, if stimuli need to be released from the hand to explore them one by one, this is clearly a serial strategy. There is, however, no clear distinction between serial and parallel strategies. It can be seen as a continuum of more or less serial behaviour. Indeed, a range of search slopes have been found in visual search (Wolfe, 1998).

In the study of Van Polanen et al. (2013), we showed that the search performance could be increased if a target differed in two properties from the distractors compared to a single property. This integration effect was demonstrated for the combination of shape and texture, namely when the features were smooth and spherical. In this case, both features are non-salient (see Plaisier et al., 2008, 2009b; Van Polanen et al., 2013). If participants searched for a smooth sphere among rough cubes, they had shorter reaction times than when the target was a smooth cube or a rough sphere. In the latter cases, only texture or shape information was available as a cue, respectively, whereas both properties distinguished the target from the distractors in the former case. It was concluded that texture and shape could be integrated in a search task. A question that remained was how this integration takes place. It could be that the two properties are combined into a single conjunction target, or that participants search simultaneously and independently for two properties and perceive the target as soon as one of the two is felt. In the latter case, the properties that are perceived will both trigger a response that the target is present. In this way, the integration effect can be explained by the fact that the fastest signal of either property can be used, resulting in an overall decrease in reaction time. Models that favour this option are often called race models, since the two signals independently 'race' for the first response. On the other hand, instead of simultaneously searching for two properties, the two signals might be combined to achieve better performance than just the faster of the two. This combination of signals might already take place at the perception stage, where the two separate properties are somehow pooled to trigger a response. Because of the combination of signals, the search can be performed faster. This option can be termed as coactivation.

In summary, the integration effect might be caused by an enhanced performance because there are two signals that can race for the decision response or, alternatively, there might be a coactivation of the two signals. To be able to distinguish whether race models or coactivation can explain the integration effect, the race model inequality as formulated by Miller (1982) can be used. If a race model is valid, then the following inequality must be satisfied:

$$P(\mathrm{RT} < t | S_1 \text{ and } S_2) \leq P(\mathrm{RT} < t | S_1) + P(\mathrm{RT} < t | S_2) \tag{5.1}$$

Here, $P(\dots)$ represents the cumulative probability function that a target is detected at a certain reaction time RT. Furthermore, $t$ is the time since the start of the search and $S_1$ and $S_2$ are the two stimulus properties. On the left-hand side, the probability distribution for the condition with two properties is displayed. The right side represents the sum of the probability distributions of the reaction times for the two single-property conditions. In all race models, the probability distribution of the combination of two properties cannot be higher than the sum of the probability distributions of the two separate signals. So, if this inequality is violated, all race models can be rejected. This race model inequality can be seen as an upper limit boundary, in which no assumptions about a possible correlation between the two signals are made. A special case, in which signals are assumed to be processed stochastically independent, states that the probability a target with two properties is detected is 1 minus the chance neither of the single properties is detected. This can be written as:

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$$P(\mathrm{RT} < t|S_1 \text{ and } S_2) = 1 - (1 - P(\mathrm{RT} < t|S_1)) \times (1 - P(\mathrm{RT} < t|S_2)) \quad (5.2)$$

When slightly rewritten, this equation is identical to the one described in Meijers and Eijkman (1977):

$$P(\mathrm{RT} < t|S_1 \text{ and } S_2) = P(\mathrm{RT} < t|S_1) + P(\mathrm{RT} < t|S_2) - P(\mathrm{RT} < t|S_1) \times P(\mathrm{RT} < t|S_2) \quad (5.3)$$

This equation resembles inequality 5.1, except that the two signals are assumed to be processed independently.

In the present paper, we investigated whether the integration effect of shape and texture that was found (Van Polanen et al., 2013) simply consisted of a simultaneous search for two properties or for a combination of the properties. To answer this question, the original experiment was redone with a new condition added. In this added condition, there were two different targets: one that differed in one property from the distractors, and another that differed in another property from the distractors. If one would search simultaneously for two properties, then equally fast reaction times would be expected as in the condition with one target that differed on two properties from the distractors. In fact, faster reaction times might be expected, because with a higher number of targets the chance to feel a target instead of a distractor is larger. If, however, the combination of two properties in a single target is more beneficial than having them apart, faster reaction times can be expected in that condition. To determine whether a race model can explain the integration effect, the race model inequality 5.1 was evaluated. Although in previous studies the race model analysis was used on shorter reaction times, it can still be used to distinguish between combined and separate processing. If coactivation explained the integration effect, the inequality would be expected to hold for the condition with two targets, but not for the condition with a single combination target. If a race model explained the effect, the inequality would be expected to hold for both conditions.

## 5.2 Methods

### 5.2.1 Participants



Twenty strongly right-handed participants (12 females) took part in the study, with a mean age of 21 ± 3 years. The handedness was tested with Corens test (Coren, 1993). Two other participants were removed from the analysis, because of a too high percentage of errors in one condition (≥ 20%). This low accuracy rate makes the reaction times unreliable, although the results of both participants were not different from those reported below. Initially, the study was run with 10 participants. After analysis, it appeared that there were quite some individual differences and the results were inconclusive. Since the results from the previous study with the same set-up (Van Polanen et al., 2013) were not replicated completely, we wanted to be sure the power was large enough. Therefore, another 10 participants were measured, resulting in a total of 20. Participants were naive to the purpose of the study. Prior to the experiment, they gave their written informed consent. They received a fee for their participation. The study was approved by the Ethics Committee Human Movement Sciences (ECB).

## 5.3 Apparatus

Four different stimulus items were used in the experiment: rough spheres, rough cubes, smooth spheres and smooth cubes (similar to Van Polanen et al., 2013). The spheres were wooden beads (Pipoos, arts and crafts store) and the cubes were also made of wood. The rough stimuli were made by gluing small pieces of sandpaper (Bosch, P60) on them. The diameter and volume of the spheres were ~15 mm and ~ 1.8 $cm^3$ and the edge length and volume of the cubes were ~12 mm and ~1.7 $cm^3$. All stimuli weighted about a gram. The stimuli could be hung from a piece of string, which was glued to each stimulus. The stimuli were presented in a bundle, which always consisted of 7 items. This number was chosen because larger differences between conditions can be expected with a larger

**Table 5.1:** Overview of the conditions. The symbols in the last column illustrate the targets (circles: spheres; squares: cubes; open symbols: smooth; filled symbols: rough). The distractors were always rough cubes (■)

| Condition | Target(s) | |
|---|---|---|
| sphere | Rough sphere | ● |
| smooth | Smooth cube | □ |
| combi | Smooth sphere | ○ |
| 2-targets | Rough sphere and smooth cube | ●□ |



number of items and this was the largest number that could fit comfortably in the hand. A bundle could contain a target (target-present bundle) or not (target-absent bundle). The distractor items were always rough cubes, so a target-absent bundle contained 7 rough cubes. A target-present bundle contained rough cubes and one or two targets, dependent on the condition. The conditions and target kinds are listed in Table 5.1. Targets are also pictured in Figure 5.1.

The experimental set-up was the same as in Van Polanen et al. (2012b, 2013) and is shown in Figure 5.1. A stimulus bundle was hung onto a hook that was attached to a tripod. The tripod was placed on a weighing scale (Mettler Toledo SPI A6). When the participant lifted the stimuli, this resulted in a weight change and this started the reaction time measurement. The measurement was ended by a vocal response, which was recorded by the microphone of a head-set, placed on the participants head. The delay of the weighing scale (90±20 ms, as measured by Van Polanen et al., 2012b) was added to the reaction time. The sample frequency was 14 Hz.

### 5.3.1 Task and procedure

As mentioned above and displayed in Table 5.1, there were four different conditions: sphere, smooth, combi and 2-targets. In the first three conditions, only one target was present: a rough sphere, a smooth cube or a smooth sphere, respectively. In the 2-targets condition, there were two targets, and these were always both present or not at all. The order of the conditions was randomised among participants, but with the following restrictions. First, the condition that was started with was divided equally among the participants. Second, each condition must follow all others at least once, to make sure all possible orders were used.

The task in each condition was about the same. Before the start of a condition, the participant was visually shown the target and the distractors. It was also stated whether the target differed in roughness, shape or both and that there would always be 7 items.

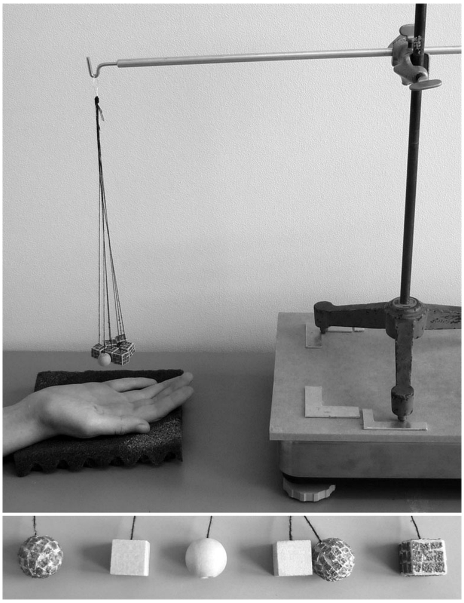

**Figure 5.1:** The experimental set-up. A bundle hangs from the tripod that is placed on the weighing scale. The close-up below shows the targets for the four conditions: sphere, smooth, combi and 2-targets, and the distractor in all conditions.



They were told they had to determine whether the target was present or not, and that they had to do this as fast as possible, but also with as little mistakes as possible. In the 2-targets condition the two targets were visually shown, and they were told that either both targets were present or none. So, if one of the targets was felt, the participant would know there were targets present. During the experiment, the participants wore a blindfold. They responded whether a target was present by calling out the Dutch equivalents of "yes" or "no". Before each trial they had the back of their hand flat upon a cushion. They were instructed to lift their hand and grasp all stimuli. After that, they could manipulate the items in any way they preferred. They were also allowed to drop items out of their hand, but it was mentioned that they should use the strategy that they thought was the fastest and most accurate for the task. Before the start of a condition, they performed at least 20 practice trials. In the practice session, they could get accustomed to the stimuli and try out different strategies. Practice trials were continued above 20 if necessary until at least 10 trials in a row were answered correctly or until a maximum of 35 trials.

In each condition, 20 target-present trials and 20 target-absent trials were performed in a randomised order. The location of the target was random, at different positions in the bundle. Participants received feedback about their answer. Incorrect trials were repeated at the end of the condition. All conditions were carried out in one session, with a short break between conditions.

### 5.3.2 Analysis

Only trials that were answered correctly were included in the analysis. Outliers in the reaction times that were above or below 3 standard deviations from the mean were removed. In addition, reaction times below 300 ms were considered anticipation or measurement errors. Only 8 trials (0.25%) were removed. Mean reaction times were then calculated for each condition and separately for target-present and target-absent trials.

The reaction times between the conditions were compared with an analysis of variance (ANOVA). To see whether a difference existed between the first 10 and the last 10 participants, a between factor group was also included. So, a 2 (group) × 4 (condition) × 2 (target presence) mixed ANOVA was conducted, with group as between factor and condition and target presence as within factors. No effect of group was found, only an interaction between condition × group, ($F(3, 54) = 3.0$, $p = 0.039$). Since there was no basis on which a difference between the two participant groups could be assumed and because the absence of a main effect, no further analyses between the groups were made. A 4 (condition) × 2 (target presence) repeated measures ANOVA was then performed on the reaction times. Post-hoc tests were performed using paired-sample $t$-tests. Planned comparisons were used with a Bonferroni correction, because only certain comparisons between conditions are of interest. The two conditions sphere and smooth were compared to combi to evaluate the effect of integration. To investigate whether the search was faster if two properties were combined in a single target, the conditions combi and 2-targets were also compared. We defined a difference between two conditions as a difference over the pooled results for target-present and target-absent trials (similar to Van Polanen et al., 2013), as these were randomly mixed in a condition and participants did not know which trial type they would encounter. The $\alpha$-value was set at 0.05. If the sphericity was violated according to Mauchly's test, a Greenhouse-Geisser correction was performed.

Furthermore, the number of incorrect answers was counted. A percentage was calculated by dividing the number of errors by the total number of trials plus the number of errors. In addition, it was scored whether participants dropped items out of their hand. The proportion of trials in which this behaviour was seen was calculated. This can be used as a measure of exploration strategy (Plaisier et al., 2009b; Van Polanen et al., 2012b, 2013). The data for these proportions were not normally distributed. Therefore, a Fried-

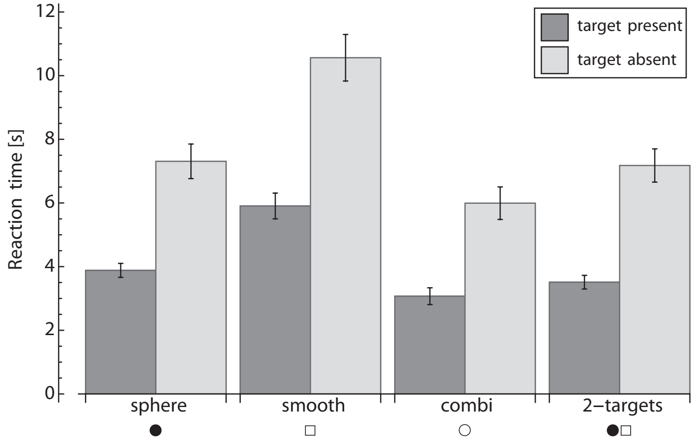


**Figure 5.2:** Reaction times for each condition, separately for target-present and target-absent trials. Symbols underneath the bars indicate the target(s) (circles: spheres; squares: cubes; open symbols: smooth; filled symbols: rough). Error bars are standard errors of the mean.



man ANOVA was performed on the conditions, for target-present and target-absent trials separately. Post-hoc tests were performed with Wilcoxon Signed Rank tests with a Bonferroni correction[1]. The same planned comparisons as for the reaction times analysis were made.

For the calculations for the race model, the methods described in Ulrich, Miller, and Schröter (2007) were used. Their method to account for possible duplicate reaction times was used. The cumulative probability functions of the reaction times were calculated for each condition for the target-present trials. The probabilities of the two single-property conditions (sphere and smooth) were summed to get the right side of inequality 5.1. This distribution was compared with the distribution of the combi and the 2-targets conditions at 10 percentiles: 0.05, 0.15, …, 0.95. The values were compared with paired-sample $t$-tests at each percentile.

## 5.4 Results

### 5.4.1 Reaction times

The reaction time data are illustrated in Figure 5.2. The 4 (condition) × 2 (target presence) repeated measures ANOVA revealed main effects of condition ($F(2.1, 40.6)$ =

[1] A conservative correction was used, where the correction was for the 3 target-present and 3 target-absent comparisons together (6 comparisons total).

**Table 5.2:** Percentage of errors in each condition.

| condition | target present (%) | target absent (%) |
|---|---|---|
| sphere | 6 | 0 |
| smooth | 9 | 0 |
| combi | 7 | 0 |
| 2-targets | 7 | 0 |

$39, p < 0.001$) and target presence ($F(1, 19) = 148, p < 0.001$), and an interaction between condition × target presence ($F(3, 57) = 11, p < 0.001$).

The planned comparisons for the effect of condition indicated that participants were slower in the sphere condition ($p = 0.025$) and in the smooth condition ($p < 0.001$) when compared to the combi condition. Furthermore, the reaction times in the combi condition were significantly lower than in the 2-targets condition ($p = 0.038$). The effect of target presence indicated that participants were slower in target-absent trials than in target-present trials.

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The interaction effect revealed no new interpretations. Post-hoc tests indicated that there was a difference between combi and smooth when the target was present and when it was absent (both $p$s $< 0.001$). Furthermore, post-hoc tests showed that target-present trials had lower reaction times than target-absent trials in all conditions (all $p$s $< 0.001$).

### 5.4.2 Errors

As can be seen in Table 5.2, more errors were made in the target-present trials than in the target-absent trials. This is usually seen in search tasks, indicating it is more likely to miss a target than to perceive one that is absent.

### 5.4.3 Search behaviour

The percentage of trials in which an item was dropped is shown in Figure 5.3. This behaviour was more often seen when a target was absent. It is clear that all conditions show some kind of serial strategy, although the values seem somewhat lower in the combi condition. The Friedman ANOVA revealed a significant effect of condition for target-present trials ($\chi^2(3) = 26, p < 0.001$) and for target-absent trials ($\chi^2(3) = 21, p < 0.001$). Post-hoc tests indicated that the percentage of trials with dropped items was significantly higher in the sphere condition than in the combi condition (target present: $p = 0.025$, target absent: $p = 0.019$). Also the smooth condition had significantly higher percentages than the combi condition (target present: $p = 0.003$, target absent: $p = 0.006$).

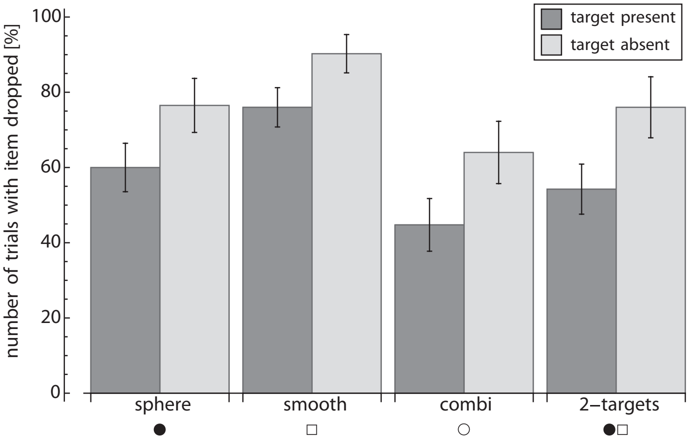


**Figure 5.3:** Percentage of trials in which one or more items were dropped. Symbols underneath the bars indicate the target(s) (circles: spheres; squares: cubes; open symbols: smooth; filled symbols: rough). Error bars indicate standard errors.



### 5.4.4 Race model calculations

The probability functions for the combi and 2-targets conditions and the race model from inequality 5.1 are presented in Figure 5.4A. If any point from the combi or 2-targets condition falls in the grey area and thus to the left of the race model, inequality 5.1 is violated. The 2-targets condition had higher reaction times than predicted by the race model for all percentiles. For the combi condition, only the first and the second percentiles showed a lower value than the race model. However, these points were not significantly different from the race model, so inequality 5.1 was not violated.

To see whether the model of independent parallel processing could describe the reaction time probability distributions, also equation 5.3 was evaluated. This is also shown in Figure 5.4A. It seems that the independent parallel processing model fitted the combi condition, but not the 2-targets condition. In Figure 5.4B, this is shown by plotting the combi and 2-targets conditions against the independent parallel processing model. As can be seen, the values of the combi condition lie more or less on the line of equality, whereas the values for the 2-targets condition always lie above this line. To test the difference between the model and the conditions, the mean reaction times from each curve were calculated for each participant. These means were compared to the model in a paired $t$-test. The combi condition did not differ from the model ($t(19) = -0.19$, $p = 0.85$) whereas the 2-targets condition was significantly higher than the model value ($t(19) = 2.9$, $p = 0.010$).

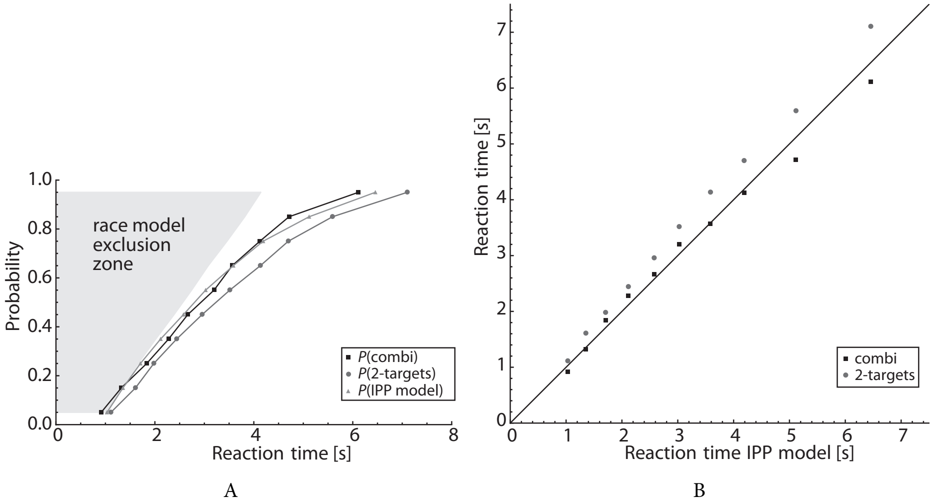


**Figure 5.4:** The probability distributions for target-present trials are plotted in A. Symbols are drawn for the combi condition (squares), the 2-targets condition (spheres) and the independent parallel processing model (IPP model, triangles). The grey area represents the area where all race models can be rejected. Points that fall in this area violate the model. In B, the same data points at the 10 probabilities of the combi and 2-targets conditions are plotted against those of the IPP model. The drawn line represents the line of equality, where $x = y$.

## 5.5 Discussion

Previous research has shown integration between various properties in visual search, where some found evidence for coactivation (e.g. Krummenacher, Müller, & Heller, 2001, 2002; Miller, 1982), whereas others did not (e.g. Monnier, 2006) and one found coactivation for some feature combinations but not for others (Poom, 2009). Recently, an integration effect between shape and texture was shown in haptic search (Van Polanen et al., 2013). When the target to be searched differed in two properties from the distractors, search performance was better than in the two single-property conditions. A baseline finding of the current study is that the integration effect we found in that previous experiment was replicated. The condition where two properties, shape and texture, were combined in one target resulted in shorter reaction times than the conditions where the target could only be distinguished from the distractors in either shape or texture alone. Furthermore, the condition with two combined properties showed less serial search behaviour than the single property conditions as evidenced by a lower percentage of trials in which items were dropped.

The main purpose of the current study was to further investigate the nature of this integration. Basically, two possible explanations were proposed. The enhanced performance could be caused by an overall faster outcome of a race between the two properties: the race model. If two properties are present in the target, an observer can respond as soon as one of the two is felt. With some variation in the signals, the faster of the two signals can be taken, resulting in an improved performance with two signals. A second possible explanation is that the two properties are combined and because of this combination a faster response is seen. That is, if there is coactivation, the signals are pooled to initiate an earlier response.

To investigate these possible explanations, the race model inequality (5.1) was evaluated. If the condition with two properties in a target (combi condition) is faster than predicted by the race model, this can only be explained by coactivation of the two properties. In contradiction to this hypothesis, the combi condition was not significantly faster than predicted by the race model. When a specific race model that assumes independent parallel processing was calculated, this appeared to fit the combi condition well. Thus, the integration effect seems to be explained by the independent parallel processing of the two properties and not because of coactivation. Some additional support for the model of independent parallel processing comes from neurological research, which suggests that texture and shape information are processed at different brain areas (see James, Kim, & Fisher, 2007, for a review). The result that a race model assuming independent parallel processing explains the integration effect seems to contradict models of optimal cue integration (Ernst & Banks, 2002). On the other hand, there are also studies that have found suboptimal integration (e.g. Burr, Banks, & Morrone, 2009) and race model support in visual search tasks has been found as well (e.g. Monnier, 2006; Poom, 2009). To calculate the optimal cue combination model, the reliabilities of the cues are needed. However, these reliabilities could not be estimated in the present study, so this model could not be applied to our data.

Surprisingly, the condition with two properties located in two different targets (2-targets condition) differed significantly from the model of independent parallel processing. This was not predicted, since one would expect that the two properties are processed parallel in this task, but it seems this cannot be done completely independently. The 2-targets condition differed significantly from the combi condition. An important point here is that the chance to find the target when exploring a certain item was higher in the 2-targets condition compared to the combi condition. In fact, when assuming a purely serial search that stops once a target is found, reaction times can be expected to be 33% lower in the 2-targets condition. Since the reaction times in the 2-targets condition were even *higher* than in the combi condition, it can be concluded that the combination of shape and texture in a single object is more beneficial for detection.

At first sight this difference between the conditions seems to suggest that the advantage for the single target is caused by the combination of the two properties. Also, in general, an inability to reject the race model does not mean that coactivation should be dismissed immediately, because this is a strict boundary. However, coactivation is unlikely to explain the integration effect, since the combi condition corresponded to the model of independent parallel processing. So, a more likely explanation for the difference between the combi and the 2-targets condition is that there is some cost in the search for two separate targets, since the 2-targets condition differed from the model of independent parallel processing. This cost would then explain the difference with the combi condition. One possible explanation for the loss in integration efficiency in the 2-targets condition is that participants did not search for two targets, but chose to search for a single target (e.g., the rough sphere, which seemed somewhat easier to find). Some participants reported using this strategy, although it was also observed that most participants responded to both kinds of targets. However, it is possible that sometimes a participant focussed on one of the target kinds, which could lead to a slower overall performance. Whether this was a conscious strategy or not remains unclear, but it seems that participants were unable to process two separate targets effectively in parallel.

In conclusion, the integration effect of shape and texture in haptic search is best explained by the independent parallel processing of the two properties. The integration efficiency is location specific. That is, if two properties are combined into a single object, better performance is seen than when the properties are present in two separate targets. Only when combined within a single target the two properties can be processed effectively in parallel.