Theories of Visual Search and Their Applicability to Haptic Search

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Abstract

In this review, the current status of search studies in both the visual and haptic modality is discussed, with an aim to assess the similarity of the processes involved. While recent models of visual search propose differing mechanisms explaining experimental results, it is generally agreed on that the search process consists of a pre-attentive parallel stage and an attentive serial stage. During the pre-attentive stage, basic features are examined and the information is used to guide attention towards salient items during the attentive stage, improving the efficiency of the search process. Using such models, average response times can be predicted accurately in a wide range of experimental settings. However, modeled response time distributions often do not correspond to experimental data, indicating that many current models of visual search are incomplete. Other points of discussion still remain, such as the cause of asymmetric behaviours with symmetric task designs, and the exact mechanism of top-down control.

The haptic modality of search has been studied less extensively than the visual one. Haptic experiments exhibit behaviours similar to visual search, with search efficiency dependent on target and distractor features in the same way as described for visual search. Discrepancies observed between visual and haptic search are often due to suboptimally matched stimuli between the two modalities. Due to the differences in feature dimensions, spatial constrains and experimental methods, such comparisons are difficult, and results of recent studies are not conclusive. There are, however, indications that search data are at least in part exchangeable between visual and haptic processes.

Contents

1 Introduction

The process of finding a specified item in a visual environment containing multiple distractors has been studied since the late 1970's [9, 39]. The mechanism behind this visual search has fascinated scientists as it is closely related to attentional deployment, the ability to identify and observe relevant items and features, and has a practical side that we encounter in our everyday life. The extensive literature on this topic provides a comprehensive overview of information processing during a visual search task. Multiple theories about such processing have been proposed, like the feature integration theory [39,42] or the guided search theory [45,46,50–52]. However, there are still several unresolved issues and points of discussion related to visual search processes [47,48].

Recently the study of haptic search has emerged, exploring information processing strategies during search in this different modality of perception. Although a significant body of experimental data has been acquired on the topic of haptic search [20, 25, 27, 28], no generally accepted encompassing theories have been developed. Therefore, theories of the visual system have served as basis for understanding haptic search [19, 25, 27] and developing experimental methods. However, several experiments show discrepancies between the results in the visual and haptic modality obtained from similarly set up tasks [23, 25].

This leads to the following question: to what extent and in what way are the theories developed for visual search applicable to search in the haptic modality? In this literature review, we describe several prominent theories of visual search and the stages of processing proposed. In addition, we provide an overview of the current findings in the field of haptic search in order to facilitate a comparison between search in these two modalities, and determine the relevance of visual search theories in the field of haptic search. The review discusses differences and similarities in processing and attentional control on a theoretical level, as well as differences in the experimental methods due to the different modalities in which the search is performed.

1.1 Aim

The aim of this review is to evaluate the state of current models of visual search, especially in the context of a possible unified information processing mechanism that would be independent of feature type or acquisition methods. While a definitive answer is not to be expected at this point considering the unresolved issues in a single modality search alone, it certainly would be worthwhile to study similarities between visual and haptic search in order to find shared underlying principles.

2 Visual Search

In order to compare different modalities of search, it is important to have an appropriate point of reference. Due to the extensive study and literature of visual search, it is used as such a reference to compare haptic search to. Information on visual search is provided in the following sections, starting with a description of visual search theories and models. This is followed by an account of the methods employed to study visual search, and applicable to search in general. Lastly an overview of visual search results is provided, not to validate the work done on visual search, but mostly to illustrate the patterns and variations therein observed in visual experiments.

2.1 Theories of Visual Search

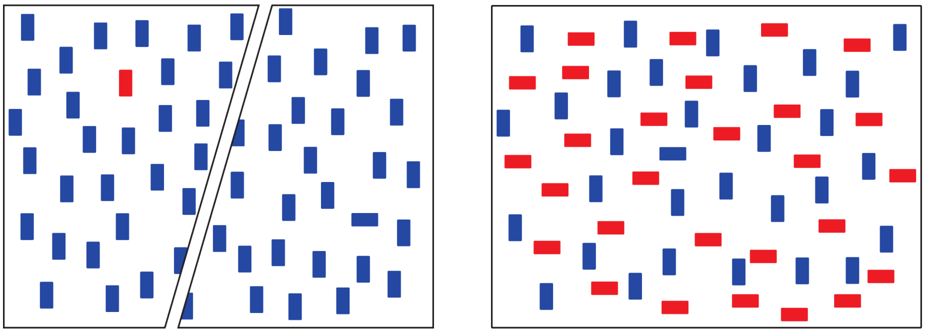
In this section several theories of visual search are discussed briefly to provide information on the mechanisms these theories propose. For a detailed description and verification of the models refer to the corresponding cited articles. In addition, an overview is provided on several points of conflict between views on search processes.

2.1.1 Feature integration theory

One popular theory describing visual search processes is the feature integration theory of attention introduced by Treisman and Gelade [39], in which a hypothesis is proposed concerning the focusing of attention. That work describes two main processes that take place during search: one parallel process which is able to analyse simple features of a large number (if not all) of the items over the entire visual field, and one serial process which needs attention focused on the observed items in sequence in order to bind this information into an object representation. Deciding which process is relevant in a search scenario depends on the features of the items to be searched through. These features are individual item properties that are located within separable feature dimensions such as colour, shape etc. [53].

The parallel search process is a pre-attentive process that registers features automatically. This information is collected for each feature dimension independently and is not linked to objects which in this early stage are not yet processed. In order to assign the collected feature information to individual objects, these locations are attended to serially combining the previously observed features into separate object representations.

Within search experiments, a clear distinction is proposed between search tasks that require only a single feature dimension to be observed — "feature search", and tasks in which a conjunction of feature dimensions is to be observed — "conjunction search". These two types of search tasks (illustrated in figure 2.1) are directly related to the above-mentioned processes as



(a) Feature search for either a different colour or orientation, the target is easily discovered.

(b) A conjunction search where both colour and orientation determine the target. In this case search is less efficient.

Figure 2.1: Examples of single feature search and conjunction search.

follows: A feature search can rely on the initial parallel processing alone, because, in order to indicate whether a target item is present, only information of one feature dimension is required and this is already available after the pre-attentive parallel stage. During a conjunction search, however, feature information of multiple feature dimensions is required in order to analyse each item. This integrated information is only available for an item after the item has been attentively analysed in the serial process, thus the attentive serial processing is required for a successful conjunction search.

Possible search results obtained from a feature search and a conjunction search are illustrated in figure 2.1. The response times of single feature search are independent of the number of items presented, as all items are evaluated in parallel. During a conjunction search, however, items have to be evaluated one after the other, leading to an approximately linear increase of reaction time with the number of items presented. The process of examining search strategies based on response times is described in more detail in section 2.2.

While the above-mentioned form of the feature integration theory has served as the basis for many models of visual search, it is not considered to be an accurate account of the mechanisms behind it [8,42,47]. In several conjunction search studies, results more efficient than a self-terminating serial search have been observed [5, 42, 51, 53], which in some cases even approach results typical for single feature search. This issue has been addressed later by Treisman [42], reasoning that in some cases visual search is able to bypass the need for a slow serial processing of a subset of the distractor items. The mechanism for these efficient conjunction searches is proposed to be inhibition of a subset of the items not related to the target on the basis of the gathered pre-attentive information. In other models different mechanisms are proposed for this spectrum of efficiency of search ranging between the parallel search and serial search as originally proposed by Treisman.

Another issue in the feature integration theory is the relation between target–present and target–absent trials' reaction times [26]. The initial assumption was that a search is terminated either when the target has been found or all items have been analysed, matching an observed 2:1 ratio of reaction times. This is due to the idea that when analysing randomly, on average only half of the items have to be processed before the target is found, whereas if the target is absent, items are analysed until no items are left in a self-terminating search. This assumption, however, does not hold if there is a possibility of guiding attention to a possible target if present, as is the case with efficient searches. As an alternative, an adaptable threshold for search termination is proposed [6, 7, 45], with a magnitude in the same feature continuum as the measure which determines whether an item is a probable target. This threshold effectively results in a separation between items that will be analysed and items that will not. The threshold is adapted in consecutive trials based on the success of the previous trial.

2.1.2 Guided search

Another prominent model of visual search is the guided search model proposed by Wolfe et al. [45, 51]. In its several iterations, it aims to describe the processes involved in visual search, forming a well-specified model and describing each stage of visual search in detail sufficient to create a computational model able to simulate a wide range of phenomena that have been observed experimentally. The structure of the model bears similarity to the one described by Treisman and Gelade [39], in that it is also based on two stages: a largely parallel pre-attentive stage registering feature information for each feature dimension independently, followed by a serial stage which evaluates individual items sequentially (see figure 2.2).

The main idea behind the guided search model is that, while information of the parallel stage is not used to identify search targets during single feature search, it is used to guide the serial stage of the search to the locations most probably containing the target. This allows for efficient search of both single features and feature conjunctions whenever the initial parallel stage can provide any information on possible target location.

The guidance of the serial stage is based on feature maps that indicate salience as the sum of differences between each item and its neighbours, weighted by the distance between them, so that closer items have a greater effect. This mechanism effectively selects items that are different from their neighbours, and thus these pop out as illustrated in figure 2.3. Feature dimensions are subdivided into broad channels such as "red", "green" and "blue" for colour, or "steep slope", "shallow slope", "left tilted" and "right tilted" for line orientation, and feature maps are created for each of these channels. These feature maps account for bottom-up guidance of the serial process.

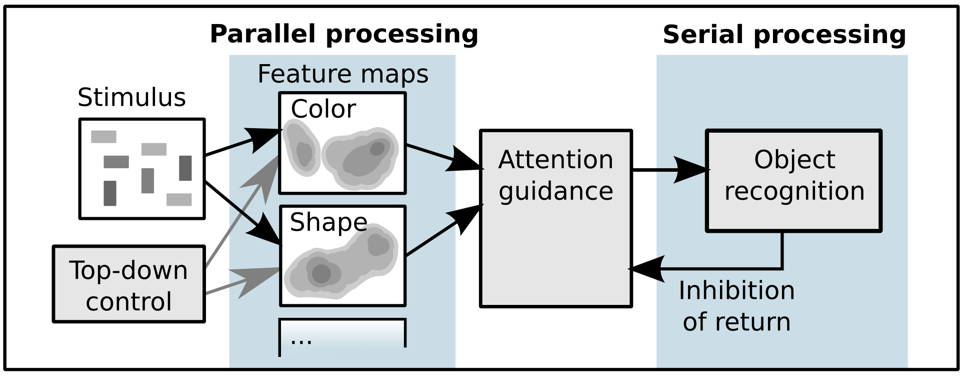


Figure 2.2: Schematic overview of a parallel and serial stage in visual search, similar to the structure proposed for the guided search model [45,51]. Feature maps containing salient locations are created from the visual input in parallel, and together with top-down selection of features guide attention towards the most salient locations in a serial manner.

In addition, a mechanism for top-down guidance is proposed, selectively modulating strength of individual feature maps or spatial locations within maps based on a priori knowledge of the search task. In this way more importance can be given to, for example, the red feature map if red is a feature discriminating the target item from distractor items. Furthermore, irrelevant feature maps can be considered less important depending on their content, and modulated accordingly.

Finally, the weighted feature maps are combined to form an activation map that, based on the previous steps, should provide a quantitative measure of importance of each location in the visual field. During the serial stage of search these locations are attended to one at a time starting from the one with the strongest signal in the activation map. When a target item is found in that location the search is terminated and the target is assumed to be present. If no target item is found in the current location, return to this location is inhibited and the next most active location on the activation map is attended to.

In case no target items are found, the search is terminated after a threshold of signal strength of the activation map is reached. This threshold is adjusted during consecutive search trials. After a successful trial it is assumed the activation map has been useful in locating the target item. In this case the termination threshold is adjusted upwards and the following search will be terminated earlier if no target is found, making the search faster for target–absent trials. In the case of an unsuccessful trial, it is assumed a target item was present, but search was terminated before that item was reached. The threshold is adjusted downwards so that the following search will be terminated later if no target has been found, allowing for

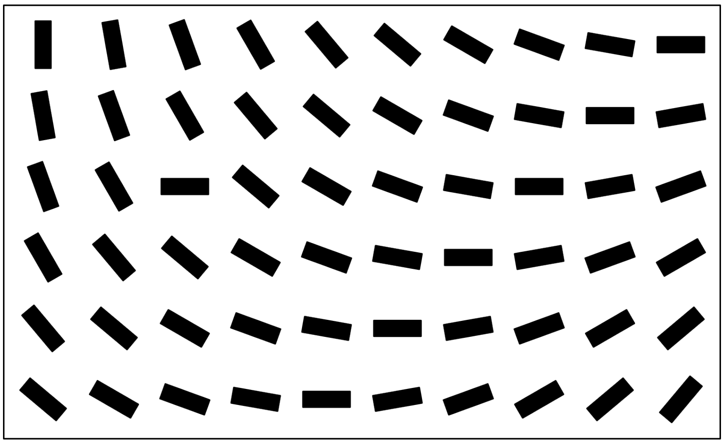


Figure 2.3: Item saliency depends on differences relative to neighbouring items, not on absolute features. The image contains multiple horizontal bars, however one attracts attention more than the others.

locating a target item when it is less salient.

A second time-based termination threshold is implemented, which aborts the search after a large number of items are examined dependent on the total number of items displayed, and independent of the saliency of the remaining items. In these events, a target–absent response is given for the majority of the trials, with only a small number of target–present responses (3% in the Guided Search 2.0 model [45]). This allows the possibility of false positive responses, and is modelled to match the small statistical chance of false positive responses in experimental data.

2.1.3 Feature maps and guidance

Besides the guided search model, there are many models that include feature maps as an intermediate step towards a general topological saliency map being able to control attention in a serial evaluation of items [4, 5, 12–14, 16, 17, 33, 37, 38]. Some notable examples include an attention network model by Koch and Ullman [15] which describes a similar process, additionally detailing feature integration for selected items, and further attention guidance by proximity and similarity. Another one is a related computational model of saliency-based visual attention by Itti et al. [13, 14] based on early vision in primates, having each feature map consisting of several low-pass filtered representations. This bears similarity to the feature gate model [4] in which topological gating is performed in a hierarchical manner throughout the feature maps. While these models differ in their specific details of implementation, the similarity in approach indicates agreement on the general structure of information processing during visual search.

It is interesting to consider how such a feature map based model might handle conjunction searches with features in multiple feature dimensions identifying a target. In some cases top-down selection or inhibition of feature dimensions or categories might enhance search efficiency. In the worst case scenario, neither of the feature maps will provide any useful information of a specific item being more salient than the others. This reflects the experimentally observed increased difficulty of conjunction search.

2.1.4 Visual search behaviour

In order to validate models of visual search, a number of phenomena encountered in search experiments are provided [47, 50], which a model of visual search should be able to explain:

1. The time required to perform search is dependent on the number of items presented.
   Specifically, due to the serial nature of the search, reaction times should increase with an increase in the number of distractor items.

2. Target presence or absence influences response times.
   Different models provide different accounts for this occurrence, although logically a target–absent search would be terminated only when the probability of finding a target is very low. In a similar target–present search, this would mean there is a very large probability of having found the target item before this point is reached, leading to a shorter response time for target–present trials in general.

3. Target–distractor similarity affects response times (figure 2.4a).
   This is due to the lower saliency of similar items reducing the pop-out effect guiding attention to probable targets and reducing the efficiency of the search.

4. Distractor heterogeneity affects search efficiency (figure 2.4b).
   In this case, similar to the previous one, differences between distractor items increase the salience of those irrelevant items therefore interfering with the guidance of attention.

5. Whenever there are distractor items with features deviating in both directions from the target feature in the feature continuum, search times increase (figure 2.4c).
   This again can be attributed to an increased salience of non-targets due to distractor–distractor differences larger than the target–distractor differences in the relevant feature dimension.

6. Search asymmetries occur when a different result is obtained by switching the target and distractor features (figure 2.4d).
   Assuming both experiments remain symmetrical, the asymmetry is expected to be due to information processing. This is a much discussed

issue. Wolfe suggests observed asymmetries are due to a difference in the ability to select each feature as a target for top-down control.

7. Categorical grouping differences imply that when a target is unique in one category of a feature dimension, then search is faster than when distractor items share the same category.
   Within the guided search model, the reason for this is that if the target feature is categorically unique, a higher weight can be assigned to that particular feature map, thus enhancing guidance towards the target.

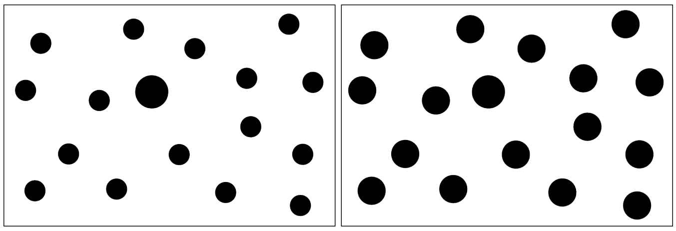
8. Guidance of attention towards the target item.
   The cornerstone of among others the guided search model, causing attention to be shifted to the more salient locations of the visual field as determined from the bottom-up and top-down activations. This provides a mechanism for efficient searches with a serial component.

When looking at for example the previously discussed guided search model, these phenomena are considered to be predicted by the mechanisms described in the model as follows: Points 1 and 2 are mainly effects of the serial nature of the search task, where fewer items to evaluate means a lower response time, whether this is because of a lower number of total items, efficient guidance or termination criterion. Items 3 through 7 are concerned with the creation of feature maps based on item salience in specific feature dimensions, which can efficiently guide attention to possible target locations. Guidance ultimately links the creation of a suitable activation map to a reduced number of items to evaluate leading to the observed decrease in response times.

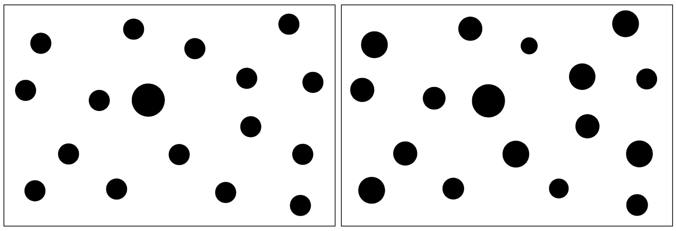
2.1.5 Search asymmetries

A significant deal of the effort put in unravelling the processes behind visual search has gone to understanding search asymmetries. As described earlier, search asymmetries occur when in a search task the target and distractor identities have been switched symmetrically but the results obtained from both tasks differ significantly. Studies on search asymmetries [49] have shown that there are certain features which are more salient than others within the same feature dimension. Such observations have been used to investigate what features guide attention during search [41]. The logic behind it is that the presence of such a basic feature is easier to detect than the absence of it, causing differences in reaction times. These basic features are discussed further in section 2.3.

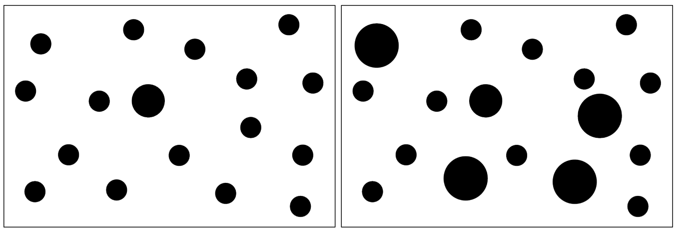
While such search asymmetries are observed in many cases, there are studies in which the asymmetric result is caused by an asymmetric experiment and the asymmetry is not due to different salience of features [35]. One often overlooked detail is the identity of the background [36]. The presence



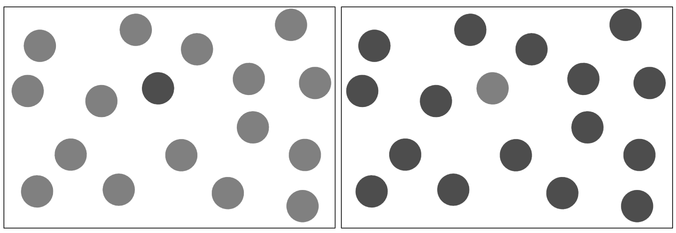
(a) Effects of target–distractor similarity. When the target is similar to the distractors (right) search is less efficient.



(b) Effects of distractor heterogeneity. When there is variation in the distractors (right) search is less efficient.



(c) Effects of target flanking. When there are distractors both smaller and larger than the target (right) search is less efficient.



(d) Effects of search asymmetry. With certain features, when target and distractor identities are switched search efficiency is affected.

Figure 2.4: Examples of different behaviours encountered in visual search.

of a background besides the target and distractors can lead to an asymmetric experiment. Whenever the features of target and distractors are switched symmetrically, the background should be changed symmetrically as well. In cases where the background is not changed, a situation exists in which the relations between background– and target features and between background– and distractor features are not preserved, and the saliency of these items is changed. This is similar to the observation of decreased saliency when distractor items have features on both sides of the target feature in the feature dimension (see section 2.1.4).

Most models of visual search concentrate mainly on the identity of target and distractors, sometimes overlooking the importance of the background used. It is therefore important to be aware of such effects, especially when looking at search asymmetries. A saliency-based model of visual search is proposed that covers such effects [34, 35].

2.1.6 Alternative theories

There exist many other theories describing visual search, some proposing mechanisms significantly different from the ones discussed previously, others adapting minor details of a process in such a way that it fits experimental data better. Due to the focus of this review other models will not be discussed in depth. Still, to provide some perspective on the matter, here are some notes about other views. In contrast to the theories discussed in the previous sections, there are proposals of different structures of the mechanisms involved. One such theory is the search via recursive rejection [10]. It describes a neural net model with a single parallel process, which discards groups of irrelevant objects. This and similar theories provide an account of visual search that is able to explain inefficient search without the involvement of a serial process.

Concerning the guidance in attention by information gathered in the pre-attentive stage, there is a general agreement among several theories (see section 2.1.3) that visual attention guidance consists of two components: a bottom-up component that merely registers salience of items based on their environment in feature maps, and a top-down component that is able to selectively modulate the importance of feature maps based on a priori knowledge of the target item. For example, these two components guide attention deployment in Wolfe's guided search model, and seem sufficient to describe several phenomena observed in experimental data. There is, however, a third component proposed [44] that might be able to guide attention efficiently even in the absence of bottom-up feature salience, or top-down control. In this attentional engagement theory, non-target items are suppressed and this suppression is spread across similar items.

2.2 Experimental Methods

The methods used to discriminate between the different scenarios, such as parallel or serial search, are based mainly on reaction times of subjects instructed to indicate the presence or absence of a target item among distractor items [47]. In the context of search processes, search efficiency is an indirect measure of how suitable a search strategy is for identifying a target item among distractor items in a search task. If the task is easy or the system is well suited for the task, then an efficient search is performed and the time necessary for a response whether a target is present or absent in the display is relatively short.

Response time With the models described earlier, an assumption is made that the parallel processing of the visual stimuli is independent of the number of items presented and the time necessary to complete this stage of the search process remains constant for a search task with varying item numbers. The serial processing of individual items is presented as a process that takes a certain amount of time per item, and the total time needed to complete the serial search stage is proportional to the number of items that need to be attended to until either a termination criterion is reached or the target item is found. This simplification of the timing of search processes provides a link between theory and experimental results [45].

A large group of experiments studying search have been performed in such a way that an average response time can be obtained as function of the number of distractor items presented [47, 53]. This response time has, as mentioned, two components: a delay corresponding to the pre-attentive parallel stage independent of the number of items presented, and a delay per observed item in the serial stage of the process. Note that the number of items analysed during the serial stage is often only a subset of all items containing only the most salient ones. Figure 2.5 shows an example of such results from one of the early studies of Treisman [39].

There are several variables when determining the timing of these processes. For example, in Wolfe's guided search model [45] a fixed time of 400 ms accounts for a possible primary stage and overhead. An additional $50\,\mathrm{ms} \pm 25\,\mathrm{ms}$ is added per item in the secondary stage. The number of items N that are processed is determined from the model considering target–distractor similarity and top-down control. The resulting response time can be verified with appropriate experimental data. The time values used in this model are estimates based on other studies of response times, they might however be task-dependent. More accurate values for the delays due to these processes can be obtained when performing a very efficient mostly-parallel search largely eliminating the second serial component.

A relatively new development is the study of response time distributions of search tasks [54]. These have been found to show very task-specific be-

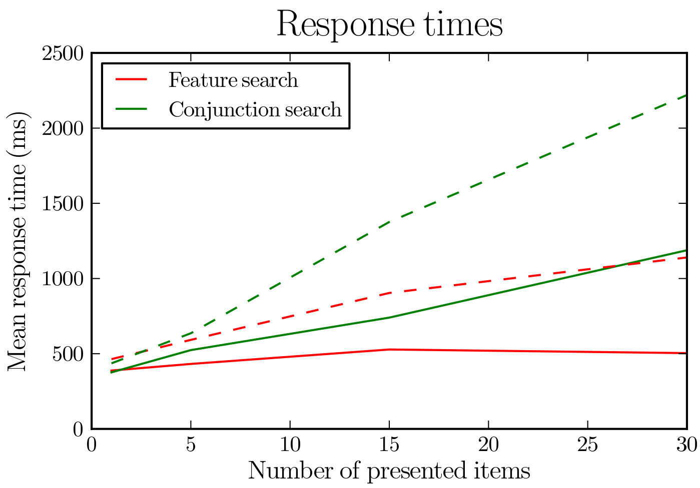


Figure 2.5: Search response times compared between feature and conjunction search as function of the number of distractors. Target–absent response times are indicated with a dashed line. Adapted from Treisman [39]

haviour for several types of tasks that have been extensively studied, and give a new perspective to understanding search processes in the human brain. Current models of visual search often provide a correct mean of response time to search tasks, but the response time distribution does not match that of experimental results. This discrepancy indicates that the mechanisms proposed in these models are not an accurate representation of the actual processes they try to model. Several models are being adapted to provide results that match experimental observations in this new measure [43, 50].

Illusory conjunctions Another often used method is to present the display for a limited amount of time, and recording the error rates. Again, by varying the number of distractor items presented, the error rates indicate in which trials the short presentation time was sufficient to perform search [47]. This method, while efficient, provides results that are less directly related to search process timing as the previously described method. It allows, however, to observe another phenomenon – illusory conjunctions. In such cases, features are perceived correctly but the process of matching features to spatial locations in order to form objects is not performed due to time constrains. The lacking information can be accessed, according to Treisman [39], from previous knowledge or contextual information to create complete object representations. Illusory conjunctions seem a very useful phenomenon when studying search processes. However due to their complexity and task-dependency, they are less applicable when investigating general search processes. Illusory conjunctions do suggest that indeed features are observed in an early stage, but the information is integrated into objects only at a later stage of processing. This is in agreement with the discussed models of visual search in section 2.1.

Feature perception Due to the involvement of perception of the presented stimuli in a search experiment, it is not feasible to observe search processes independent of perception. Therefore, perception of task-relevant features should be considered. The perceived saliency of features influences the efficacy of the pre-attentive guiding stage, affecting the search results. It is important to know which features the system is able to discriminate between in the pre-attentive stage. A common method [47, 53] is to provide a single feature search task with sufficient contrast between target– and distractor items. When this results in efficient search independent of the number of distractors, it can be assumed that the studied feature is taken into account during the pre-attentive processing stage and possibly has a corresponding feature map created for that feature dimension. Results of such studies are discussed in section 2.3.

2.3 Visual Search Results

As different search experiments use different methods and set-ups, it is not trivial to compare data between studies. A comprehensive overview of visual search results has been provided by Wolfe [48], containing a large number of trials of varying search experiments, grouped in several broad categories such as feature searches and conjunction searches. Considering the variation of the methods used to collect the results and the broad categorisation, these results mainly illustrate a general trend and do not provide information about specific mechanisms affecting visual search. In this dataset the following is observed. The relation between target–present and target–absent trials has been presented as a ratio between the slopes of target–present or –absent trials. Over all collected data, a strong correlation between search slopes has been observed. An average ratio of about 2:1 has been measured, corresponding with results and theories from other studies [6, 26, 45]. However, for efficient searches (20 ms/item or less) this ratio is observed to be significantly higher, with mean ratios up to 5:1 [48]. Slope ratios were observed to be closer to 1:1 for displays of 8 items or less during conjunction search [26].

When comparing search slopes between feature search and conjunction search experiments, a significantly less efficient search is observed in the latter case [48]. This is in agreement with less efficient conjunction search as described in several models. In these data from a broad range of experiments, there is great variability in the individual results. Because of this, while there is a clear trend, it is not feasible to determine whether the task is a feature– or conjunction search based on the results alone.

These results illustrate two of the main phenomena in visual search: the difference between target–present and target–absent trials, and the difference in search efficiency due to a single feature or a feature conjunction search. In order to observe other features typical for visual search (as described in section 2.1.4), it would be necessary to perform specific experiments containing tasks targeting these behaviours. Such experiments have often been performed on a smaller scale and not across a broad range of experimental parameters, and thus are not discussed here.

Guiding features Besides extensive studies of visual search strategies, the actual feature dimensions in which features are perceived have been studied [40, 47, 53]. An important aspect of visual search is to understand what features can be processed efficiently, as search in the real world is not constrained to well-specified features as used in an experimental set-up. Furthermore, knowledge of the response to different features will improve the general understanding of search processes independent of the specific target– and distractor items used.

Based on the idea of feature maps being created in a pre-attentive stage of search, the features for which such feature maps exist have been investigated [53]. In search experiments, these features are able to guide the deployment of attention in subsequent processing, allowing for efficient search. Features such as colour, orientation, motion, size etc. are able to guide attention towards salient items when there is sufficient contrast to discriminate between the target and distractor features in the early pre-attentive stage of search. There are several other attributes that are possibly related to guidance, but no conclusive evidence has yet been found. These attributes do not correspond directly to the early stages of general visual processing, and are specific for the task of guiding attention [53].

The way in which these features guide attention varies between attributes. For colour, three broad categorical feature maps are proposed, containing the saliency of the red, green, and blue features, while orientation feature maps most likely contain a steep/shallow and a left/right category [45]. Another point to consider is how these features are perceived and how the feature dimensions relate to the physical attributes of the object. A study concentrating on colour features in visual search provides insight on the measures of colour similarity that affect the efficiency of the search [33].

The obtained results show general trends that match the discussed theories. Relations between the obtained results can be explained on the basis of current understanding of visual search processes. There are however variations in the results that are probably caused by task-specific differences which currently are not accounted for in visual search models. These more complex behaviours can be studied on an individual basis, but the acquired knowledge is often not applicable or easily transferable to the case of general search processes. Such variations make the use of current visual models as reference for new tasks difficult when looking further than general trends.

3 Haptic Search

Compared to the study of visual search, haptic search is an area that is still relatively unexplored. Perhaps a reason for this is the difficulty of accurately studying haptic processes. Haptic search is more complex than its visual counterpart due to several differences [21]. Firstly the haptic space is three-dimensional, this implies a more complicated system of information acquisition and spatial relations. Secondly, haptic features are more complexly defined, and different actions are required to evaluate these features. Thirdly, information acquisition is more spatially constrained as parallel acquisition is limited, in most of the relevant experiments, to the area of the hand. This, together with the slower and more complex shifts of attention in the haptic space, implies that such effects might have a significant impact on the results of haptic search experiments. This added complexity requires a better understanding of the underlying processes in order to observe the effects of search processes alone, especially when the same methodologies as for visual search are used. Currently, no theory of haptic search has been agreed on, and reasoning parallel to that in visual search models is used to describe the observed behaviours.

3.1 Experimental Methods and Results

Haptic search experiments have been performed with different set-ups to allow haptic search in various situations and with various constrains.

A haptic search task involving different stimuli applied to the fingertips of the subject simultaneously [19, 20, 25] is illustrated in figure 3.1c. In this set-up, simultaneous acquisition of stimuli from all fingers is possible. This provides the information needed to process the stimuli in parallel if such mechanisms operate during haptic search. This method allows accurate observations of parallel processing during search without effects of display exploration. There are, however, several limitations in such a constrained task. The lack of exploratory movements in search of the items to be evaluated provides a search paradigm that does not resemble haptic search in a natural environment. Spatial locations of items do not play an important role. Additionally, the available fingers limit the maximum number of items presented, prohibiting study of a broad range of distractor quantities. Studies of visual search suggest that search behaviour changes for large quantities (8 and more) of distractors [26]. Lastly, the set-up itself constrains object exploration due to limited flexibility, and the varying sensitivity and importance between fingers might influence results [21].

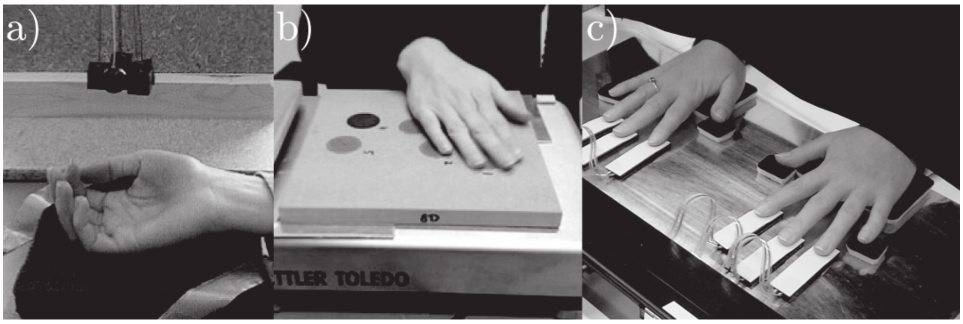


Figure 3.1: Illustration of several different haptic search tasks. a) Haptic search among suspended three-dimensional objects. b) Search of a haptic display containing patches with different roughness. c) Items with varying features applied to multiple fingertips simultaneously.

Among others, results [19] show that search slopes vary between easy (single feature) and difficult (conjunction) search, suggesting a pop-out effect similar to the one observed in Treisman's early studies [39] for feature search. Together with a 2:1 ratio between target–present and target–absent trials for conjunction search, the obtained results are similar to results obtained in visual search. Response curves are observed to be steeper for a difficult feature search, indicating that certain features are not processed as efficiently and a serial approach is used [20]. When comparing similar features in haptic and visual search [23, 25], in the case of a search for a cross among circles the haptic version appears to be less efficient than the visual one. Search for an item among empty spaces did lead to an efficient haptic search. These results show that features which guide search cannot be easily compared between the visual and haptic modality.

Another haptic search task, more comparable to the ones used in visual search experiments [27], has been used to study search and exploration patterns. In those experiments subjects were presented with a flat surface containing randomly positioned patches with different properties (figure 3.1b). Free exploration of the surface was allowed, and hand movements were recorded. Such a set-up allows for exploration of the display, possibly guided by salient features. The similarity with visual experiments allows both easier comparison and study of processes that might have both a haptic and a visual equivalent. The items have distinct locations in the space that is explored, however the search is only constrained to a two-dimensional plane. This possibly prevents findings to be easily extrapolated to search in three-dimensional space. This approach also has additional processes such as individual exploration strategies which can be studied, but also add to the variability of obtained results.

When searching for roughness patches, this method shows promising results. For feature search with large target–distractor dissimilarity, efficient search is observed. Efficiency decreases as the target and distractors are more similar. Search during target-absent trials is significantly slower compared to target–present trials. When switching the identities of the target and distractors, a search asymmetry is observed where in one case the search is less efficient than in the other.

Exploratory movement patterns suggest that in the easy search items are observed with a single hand-sweep over the haptic display. For a difficult search the subjects move from object to object in a serial fashion. In an experiment where subjects were presented with raised edge circles and crosses, search using a single finger was performed faster than search with multiple fingers [24]. In a separate study using the same stimuli, the search was found to be difficult, and it was not performed efficiently [23].

In addition to the previously described tasks where the stimuli were properties of mostly flat surfaces, several experiments [28,30] have been performed where the objects were actual three-dimensional shapes that could be examined. Such an environment allows for a haptic search task to be performed in a way that is different from the previous tasks and more appropriate for haptic search in daily life. Experiments can be performed involving exploration and object perception in three-dimensional space in the context of haptic search. This freedom of course also allows for greater variability in the results as less factors are constrained. Tasks have been performed involving both freely suspended items [28] (figure 3.1a) and items with fixed location [32].

Results from such experimental set-ups are more difficult to compare to traditional visual search experiments due to the differences in spatial configurations and dimensions, and possibly need to be investigated separately. The observations, however, suggest that also in this form of haptic search, efficient, largely parallel search is possible depending on the target– and distractor features. Additionally, effects of target–distractor similarity on response times have been observed.

3.2 Feature dimensions

A problem when comparing visual and haptic search appears to be the translation of findings in haptic search experiments to an equivalent in the visual modality [23, 25]. In order to do this, it is important to use stimuli that are equivalent in both modalities. This means that the feature spaces which are used have to be well understood in order to choose comparable features to discriminate the target from the distractors. Differences between haptic and visual features and object recognition are expected. For example, while spatially aligned edges are emphasized in the visual system, they are not suitable for the haptic system due to a low spatial acuity [18].

A study similar to the ones exploring which features guide visual search has been performed for haptic search as well [20]. Information on material properties and abrupt surface discontinuities is suggested to be available earlier than orientation and shape properties. These results are based on the efficiency of haptic search among items with features in the studied feature dimensions. As with guiding attributes in visual search, it is important to consider how the feature dimensions relate to the physical properties of the surface [2]. Studies of haptic perception are useful in this regard. Additionally, salient features of three-dimensional shapes have been studied [30]. Results show that in these complex shapes, edges and corners are more salient than curvature. This, despite the differences in object exploration, corresponds to the salience of haptic features on flat surfaces.

3.3 Asymmetry and background features

As noted before, an asymmetry was observed in experimental data of a haptic search task [27]. Taking into account the several studies of visual search where asymmetry-like effects have been contributed to the background of the display (as discussed in section 2.1.5), it is interesting to look at this example in more detail.

3.3.1 Theory

In the guided search model for visual search [45, 50], the reason for search asymmetries is a less optimal match between the target feature and one of the broadly tuned channels that categorise and separate features used for top-down control. In this case it would imply that a less rough feature might not be as easily selected by the top-down selection as the rougher feature because it does not match those channels. The features of the background, however, are not considered in this model. In Wolfe's account of expected search behaviours (section 2.1.4) a less efficient search is expected when the distractor features are on both sides of the target feature in the respective feature space.

In the original haptic experiment [27] a reduced search efficiency is observed when the target roughness is lower than that of the distractor, compared to the target roughness being higher than that of the distractor. If the smooth background does not play a role in this experiment, then it is indeed a symmetric experiment showing asymmetric behaviour. The background, however, has a very low roughness that is perceived in the same feature space as that of the target and distractor roughness. It seems logical to assume that any observed roughness influences the creation of the roughness feature map describing the saliency of items in the roughness feature space. In that case the experiment is no longer symmetric as the background roughness is not changed.

3.3.2 Method

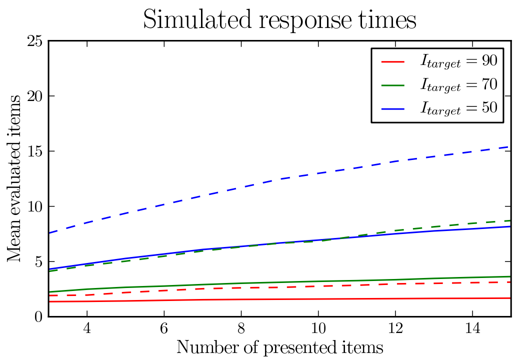
In order to investigate the possible effects of the background identity on such a task, a simulation (see Appendix A) is performed based on a simplified and modified version of the guided search model [45]. Here, instead of comparing each item to its nearest neighbour items, it is compared to every cell of the display grid including those containing no items. The roughness of the background cells is specified as lower than the roughness of any of the items. The model contains only a single feature map representing roughness, and an additional top-down component can be added to the final activation map that guides the search. Search results are expressed as the average number of items evaluated before reaching the termination threshold of activation or finding the target. This number of evaluated items is assumed to correspond linearly to the reaction time, as described in section 2.2. Item roughness values are adjusted to represent a situation similar to the one in the haptic experiment. However, parameters for the model are chosen arbitrarily and are not representative of the conditions in which the actual haptic experiment was performed. The aim of this simulation is merely to study the behaviour of search when the identities of target and distractors are reversed, taking into account the identity of the background.

3.3.3 Results

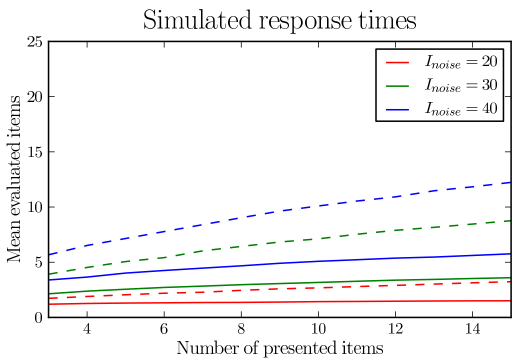
In the proposed model, there are several factors that influence the efficiency of the search. One example are item properties, where a decrease of search efficiency is observed when target and distractor identities, I_{target} and $I_{distractor}$, are closer together in the relevant feature dimension. In order for this mechanism to work in the current model, noise is added to the activation map. This noise component I_{noise}, however, can influence search efficiency when changed. Lastly, the addition of a stronger top-down component $I_{top-down}$ specific for the target item will increase search efficiency. The parameters of these three components strongly affect the efficiency of the simulated search, as illustrated in figure 3.2. An increase in the slopes of target–absent trials compared to target–present trials is observed as well.

These parameters are task-dependent and cannot be easily determined. It is possible to use an absolute measure of roughness and convert it to perceived roughness [2,3], which translates to feature intensity. The effects of noise on the process can be experimentally approximated. In this model, top-down control is not well-specified, but its effects can be determined experimentally. Considering the scope of this review and the limited data from the actual experiment, these factors will not be investigated further.

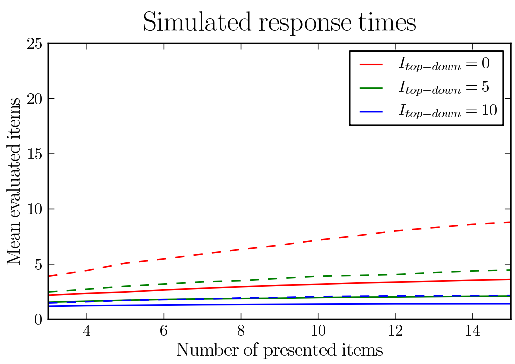
In addition to the decrease of efficiency due to target and distractor feature similarity, when target and distractor identities are reversed a decrease of efficiency is observed. This effect is studied in two conditions: no top-



(a) Effect of target–distractor similarity.



(b) Effect of internal noise.



(c) Effect of the magnitude of top-down selection.

Figure 3.2: Different factors contributing to response time slope and offset in the performed simulation of haptic search. Target–absent response times are indicated with a dashed line.

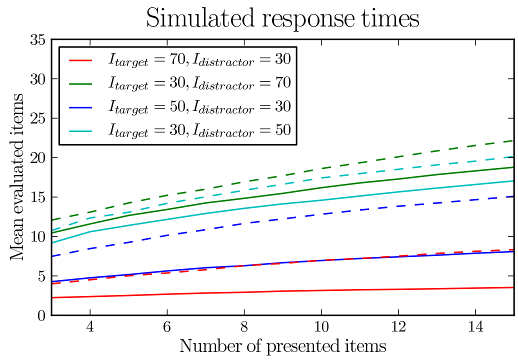
down component, and top-down selection of the target item. The results are illustrated in figure 3.3, and compared to experimental data [27]. In all cases, when the target has an identity between the distractor and background identities, search becomes less efficient, with both steeper slopes and higher y-intercepts. Top-down target selection (figure 3.3b) results in more efficient search, as the addition of top-down selection to target–distractor dissimilarity causes a stronger guidance towards the target item. Additionally, top-down selection causes a greater target–absent to target–present ratio in the case when the target identity is between the distractor and background identities, and difference in y-intercepts between target–absent and target–present trials. This behaviour more closely resembles the experimental observations (figure 3.3c).

3.3.4 Discussion

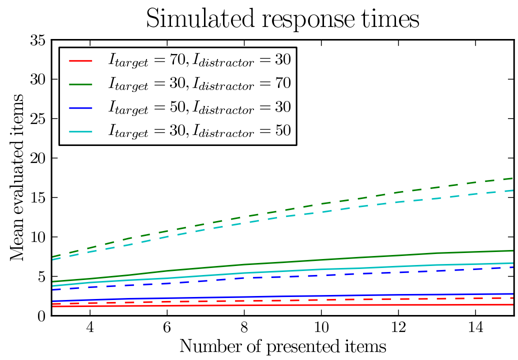
In the presented results it is apparent that the background features can influence the task performance when taken into account. This is caused by the fact that the non-target features (in this case both background and distractor items) have identities on both sides of the target identity in the feature dimension (see section 2.1.4), which increases the bottom-up saliency of distractor items due to the greater dissimilarity from the background. It reflects observations in visual studies discussed in section 2.1.5, where the use of the same background causes the experiment to be asymmetric. The simulation results of asymmetry, especially with top-down control, show behaviours similar to the ones observed in experimental data.

The top-down selection for the target item is relevant for cases with a distractor–background dissimilarity greater than the target–distractor or target–background dissimilarity, as otherwise the obtained feature map would cause attention guidance towards distractor items to be stronger than towards the target item, resulting in search behaviour less efficient than self-terminating non-guided search. In the results, this is observed as a number of items examined close to or even greater than the total number of items presented (figure 3.3a).

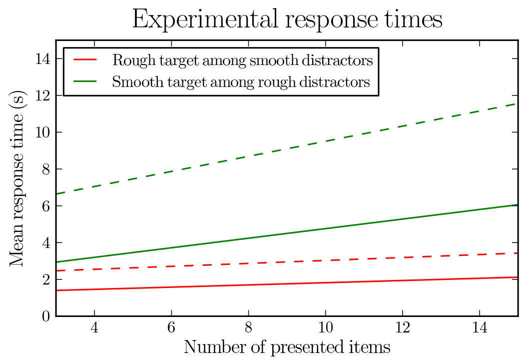
The simulation results do not provide any conclusive evidence regarding the simulated processes, and should not be considered as comparable to the original haptic experiment performed by Plaisier et al. [27]. Due to the multiple parameters influencing modelled behaviour and the linearity of the results, it is not possible to obtain realistic values for these parameters and validate the model by fitting model results to experimental data. This is merely an account of a mechanism able to generate results as experimentally observed, alternative to the one proposed by the guided search model [45, 50–52], and how it might otherwise fit in this prominent model of search behaviour. In the guided search model, no provision exists for effects of the background feature identity, and asymmetric behaviour is explained by a



(a) Simulated search asymmetry without top-down control.



(b) Simulated search asymmetry with top-down selection for the target.



(c) Experimental results of observed haptic search asymmetry. Linear fit, adapted from Plaisier et al. [27]

Figure 3.3: Observed search asymmetry in experimental results and simulated data. Target–absent response times are indicated with a dashed line.

possible mismatch between the target identity and the top-down selection of features by several broadly tuned channels. Without differences in top-down selection, the guided search model will provide identical results for $I_{target} = a, I_{distractor} = b$ and $I_{target} = b, I_{distractor} = a$ for any values a and b, as the difference between target items and distractor items will be the same. The inclusion of the background as distractor provides a mechanism explaining asymmetric behaviour not dependent on top-down selection.

Note that search asymmetry for surface roughness has been observed in other studies as well [20], and the manifestation of the search asymmetry is not specific to this experimental set-up.

3.4 Summary

The discussed results show that there is a similarity in the behaviour of haptic search and visual search. Even for such different experimental set-ups, certain phenomena observed in visual search can be recognised in these results as well. Effects of pop-out or efficient guidance to salient features have been observed in the haptic domain. Task efficiency has been linked to target–distractor dissimilarity in a manner similar to visual search, providing a range of task difficulty influencing task efficiency. Asymmetries have been observed as well in several haptic search experiments. Target–absent trials were performed slower than target–present ones, however results differ between studies.

4 Discussion

Returning to the question whether using visual search models as a basis for theories of haptic search is appropriate, we can now evaluate this based on the presented information. Two questions are considered: whether the study of visual search provides a proven and well understood structure of the information processing, and whether the same structure can be adopted when studying search in a different modality.

4.1 Accuracy of Visual Search Models

Considering the importance of the basis for understanding search and investigating it further, it is necessary to validate existing theories, and keep in mind deviations in corner cases (such as search asymmetries) which might indicate involvement of additional processes or a different structure altogether. The large body of results obtained from studies of visual search are invaluable when analysing the underlying process. Models of visual search try to describe as many of the phenomena observed in these results. There are, however, difficulties in validating a model using experimental data that has many variables which cannot be assumed to be constant between the various experiments performed [48]. Due to such variations, current theories are able to explain observed search behaviour, but are inaccurate when trying to predict experimental results. Additionally, many of the proposed models describe certain processes with well-defined mechanisms in detail, while merely providing a non-specific mechanism that might be able to account for other observed phenomena.

It appears that recent models have predominantly a structure divided in two stages (see section 2.1.3). One being parallel in which early vision features are processed, and a second stage in which the acquired information is used to select locations with high saliency for a serial or limited attention parallel evaluation and integration of features into objects. Such a structure suits experimental observations. Illusory conjunctions indicate that if the search task is prematurely interrupted, subjects are aware of the presented features, but errors occur when combining these features into objects [39]. This behaviour suggests that basic features are acquired in an early stage of search. A possible indication of a following serial stage comes from eye movements during visual search [11, 56, 57]. While it has been shown that constraining eye movements does not have a large effect on search performance [50], eye fixations are correlated with the search task. From such information it appears that attention is guided to the most salient areas of the visual display to accommodate more efficient processing of a selected smaller area. Furthermore, neural correlates support the presence of feature maps in early vision [1, 15, 55].

There is still no agreement on the details of the processes of visual search (see section 2.1.3), and models are adapted as new observations are made. For example the discriminability and specificity of response time distributions [54] has shed light on a different aspect of search results. Many current models have been able to provide accurate average response time values, but the proposed mechanisms fail to explain the distributions observed in experimental data. Only a few models [43, 50] have included mechanisms which allow for asymmetric response time distributions, and aim to explain the observed response time distributions. This not only uncovers a fault in earlier models, it also illustrates how often new discoveries will prompt further development and how such changes do not permit as of yet an agreement on one encompassing theory of visual search. As has often been stated in reviews of visual search progress, there is still no definitive answer to how visual search is performed exactly.

Despite the ever changing nature of the subject, the advanced study of visual search provides rich information on search behaviour. Many phenomena have been observed and many special cases have been studied. While there is currently no single theory of visual search that can serve as comparison for search in different modalities, the abundance of experimental observations provide a comprehensive set of behaviours that can be compared to search behaviours in for example haptic search, or used in order to validate new models of visual search.

4.2 Applicability to Haptic search paradigm

The situation with haptic search is different from that of visual search. The complexity of the subject and variations in experimental methods has led to a more dispersed set of acquired data. When looking at haptic search results however, the similarities with visual search are apparent.

Some general observations on haptic search behaviour show that despite the large differences, many similarities between haptic and visual search have been found. First of all, several studies have shown that efficient search with predominantly parallel processing of haptic objects is possible. Together with a strong linear correlation between response time and distractor count, it appears that haptic search behaves similarly to search in the visual modality, and the data are in agreement with some early theories of visual search. Slower response times have been observed in target–absent trials compared to target–present, and search asymmetries have been encountered, among others, in search among items with varying roughness [20, 27]. Also, efficiency decreased as the target–distractor similarity increased. Observations like these suggest that the same search behaviour is encountered in haptic search as in visual search. This does not necessarily imply that search processing is the same for multiple modalities, however it confirms that there is a resemblance between search in the two modalities and possibly similar mechanisms are responsible for the similarity in observed behaviour.

One of the hurdles in comparing haptic search to visual search directly is the difference in how object information is acquired due to the different modality of perception. Experimental set-ups have been designed to study specific aspects of haptic search, for example ensuring all item information is accessible simultaneously or allowing free exploration in two or three dimensions. In such tasks, there are differences in the spatial information that needs to be processed, which not always have an equivalent in visual search where retinotopic mapping seems to be universal.

Additionally, the field of view during haptic search is not as wide as in vision, leading to a greater dependence on exploration. Such differences might have an effect on haptic search behaviour that significantly influences results. Recent models of visual search [50, 52] provide a mechanism for controlling eye movement and fixation to aid the search process; these mechanisms might be similar in haptic search. Studies have shown that during efficient haptic search a single "haptic glance" is sufficient to indicate the presence of the target item, while in difficult search, items are being examined serially [27]. Furthermore, in difficult conditions haptic search is more efficient when information is acquired from a smaller area, suggesting that a serial approach is preferred. While the use of both overt and covert deployment of attention might decrease the validity of observations based on overt hand movements, as in visual search these attention shifts provide valuable information.

Comparative studies also have to take into account what features are detectable in early haptic processing, and can be used to guide attention to a possible target, thus ensuring efficient search. While some features have an equivalent in both haptic and visual form (for example line drawings), many of the guiding features of haptic search are different from those encountered in visual search. Guiding features and their dimensions have been studied in order to facilitate equivalent stimuli in comparative studies. This is especially important when considering that target–distractor similarity impacts the efficiency of a search [53], and mismatched stimuli can possibly change the behaviour of the search.

There has been limited success in comparing haptic search to visual search due to the differences outlined above. There are, however, indications that the haptic and visual modalities share some mechanisms involved in search. For example, providing visual information about either item locations, hand location, or both can improve haptic search [31]. There is an obvious relation between the visual and haptic space, and it seems that relevant information from both modalities is used during haptic search. Furthermore, visual spatial cueing to a selected location can aid haptic search [22], suggesting spatial memory is shared and guidance is transferred to be used during haptic search. It seems logical that if a search mechanism utilises multimodal information, then further processing is multimodal as well. Similarities between visual and haptic processing have also been observed in other studies [29].

The findings discussed here are not conclusive to determine whether search processing consists of multimodal mechanisms. They do, however, suggest that search behaviour is similar between the visual and haptic modality, and that processes in haptic search appear to be analogous to visual processes. As of yet there is no conclusive evidence against multimodal processing during search, either.

4.3 Conclusion

In conclusion, through the exhaustive study of visual search we have acquired a comprehensive understanding of search behaviour. Cases exist that are not yet covered in depth by current visual models, and a variety of visual search models suggest different views of information processing. While there is no agreement on one definitive theory of visual search and some results as of yet remain unexplained by current models, the general structure of visual search is well understood and in combination with the obtained experimental data it provides a good account of visual search.

The efforts to understand haptic search are more dispersed due to the complexity of the haptic modality. There are however many parallels between the haptic and visual modality of search, with differences mainly in the acquisition of information and feature dimensions. Studies suggest that spatial information during search can be shared among those modalities, possibly indicating multimodal components in search mechanisms. Due to the differences in both search paradigms and features in the two modalities, direct comparisons have not been extensively performed. With the advances in understanding both haptic and visual search behaviour and feature perception, the reliability of such comparisons between haptic and visual search tasks should improve.

In the current state of both visual and haptic search, most comparisons rely on qualitative observations of search behaviours. Better understanding of the underlying mechanisms is necessary to be able to conclusively unify search in multiple modalities.

Appendix A

Algorithm 1 Haptic search simulation

```
Create Grid of size (x_max, y_max) and cells with value I_background
Populate Grid with n_distractor cells with value I_distractor
If TargetPresent is True:
    Populate Grid with 1 cell with value I_target at location (x_target, y_target)

For each (x, y) on Grid:
    For each (i, j) in range ([x − r_NN, x + r_NN], [y − r_NN, y + r_NN]):
        r = sqrt(i^2 + j^2)
        FeatureMap_{x,y} =
        FeatureMap_{x,y} + { 0,                                           r ≧ r_NN
                           { |Grid_{x,y} − Grid_{i,j}| · (r_NN − r)/r_NN,  r < r_NN

Multiply FeatureMap by W_bottom−up
Add I_top−down component to FeatureMap dependent on item type
Add noise to FeatureMap with σ = I_noise / (sqrt(FeatureMap_{x,y}) + 1)

For each cell C in FeatureMap in order from highest to lowest value:
    n = n + 1
    If location of C is (x_target, y_target):
        Search terminated after n items, target found
    If value of C < I_TT and TargetPresent is True:
        Decrease I_TT
        Search terminated after n items, false negative
    If value of C < I_TT and TargetPresent is False:
        Increase I_TT
        Search terminated after n items, true negative
```

$Grid$: Rasterised representation of the display containing intensity values and locations of items and background
$FeatureMap$: Rasterised representation of the feature map containing feature saliency, top-down activation and neuronal noise
x_{max}, y_{max}: Rasterised dimensions of the display
x_{target}, y_{target}: Rasterised location of the target item
I: Intensity values of the different items indicated with subscripts:
$background, target, distractor$
I_{noise}: Base intensity of the neuronal noise applied to the feature map
$I_{top-down}$: Intensity of the top-down component for a given item type
I_{TT}: Termination threshold intensity which causes search termination for lower intensity values
$W_{bottom-up}$: Weight of the bottom-up component
r_{NN}: Range in which to check difference with neighbouring cells
n: The number of cells evaluated in a serial manner before target is found or search is terminated

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