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Role of facilitatory and inhibitory short-term memory mechanisms for the guidance of visual search

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Abstract

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In the visual search paradigm, participants' task is to detect the presence or absence of a target item, which is presented in an array of distractor items. Usually it is found that performance is dependent on specific properties of the visual display, for example, the number of items to be searched or the similarity between display items. However, recent research has demonstrated that memory mechanisms can also affect search behavior. Further, it was found that memory mechanisms can, in principle, be either facilitatory or inhibitory, that is, that the processing of the item locations, features, or search objects themselves can be improved or impeded, respectively.

The aim of the present thesis was to investigate the effects of (1) facilitatory and inhibitory memory mechanisms based on the positions of the search elements within the search display; (2) facilitatory memory mechanisms based on the features of search elements; and (3) inhibitory memory mechanisms based on the search objects themselves.

To access facilitation and inhibition of locations in a pop-out search task (search for a color target), a singleton target could be presented on a previous target or distractor location. Positional facilitation and inhibition was estimated by comparing reaction times to targets presented at a previous neutral position with reaction times to targets presented at a previous target (facilitation) or distractor location (inhibition), respectively. It was found that when the position of the target was repeated in consecutive trials, target detection performance was expedited (facilitation). Further, when the target appeared on a previous distractor location, target detection performance was decelerated (inhibition), but this inhibitory effect was shown to be dependent on the number of distractors presented (i.e., it was only evident for 3-element displays) indicating the capacity of the memory underlying positional facilitation and inhibition to be capacity limited to three locations (i.e., one target and two distractor locations). Moreover, with 3-element displays, facilitation and inhibition of locations were strongly dependent on practice and the (global) arrangement of the search items in consecutive trials.

To investigate facilitatory memory of stimulus features, especially to access whether facilitation results from repeated target and/or distractor features, the target defining features (orientation) in a conjunction search task (color x orientation), were repeated independently of the distractor defining features (orientation). The target was always red and unique in orientation and was presented amongst identically oriented green and differently oriented red distractors. Facilitation was assessed by comparing reaction times in conditions where neither target nor (red) distractor orientation were repeated with conditions, where both target and red distractor orientation, target orientation alone, or red distractor orientation alone were repeated, respectively. A facilitatory effect was found when the orientation of the target, together with the orientation of the red distractors, was repeated in consecutive trials. Interestingly, this facilitatory effect did not differ from the effect when only the red distractors, without the target orientation, were repeated. Further, the facilitation resulting from the repetition of the target, without the repetition of the red distractors, was only small in magnitude. Finally, evidence for facilitation was also found in target-absent trials (i.e., in the absence of any target stimulus), when the red distractors were repeated. This pattern of results indicated that facilitation in conjunctive visual search was mainly based on the repetition of the distractor, rather than target, features.

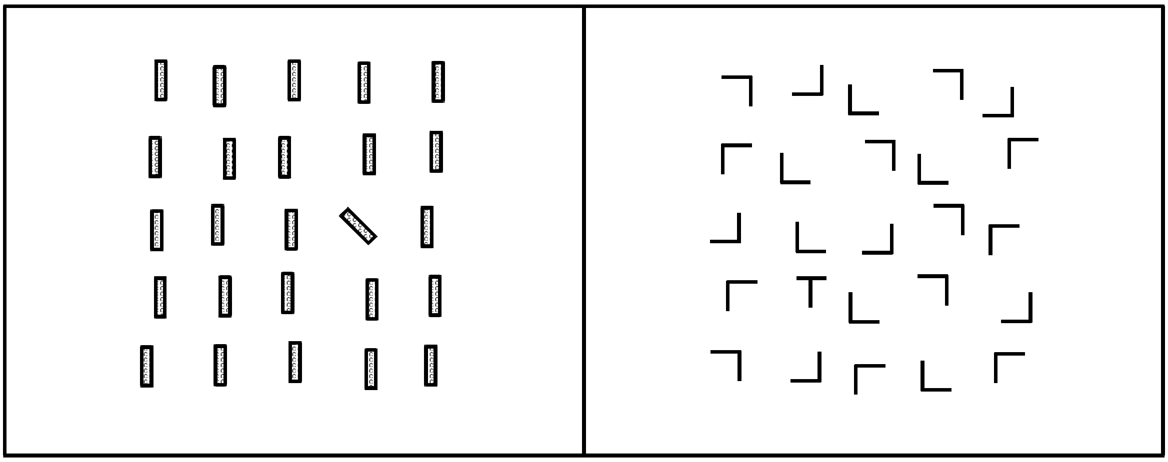
To access object-based inhibitory memory mechanisms, in a pop-out search task (with orientation-defined targets), a probe-stimulus was presented at specific display locations after the participants responded to the presence or absence of the target. Inhibition of search distractor locations was assessed by comparing response times in the pop-out with response times in a passive-viewing task (i.e., in which participants had only to passively view, rather than actively search, the display) to probes at previously empty locations with probes at previously occupied distractor locations, respectively. The results showed evidence for the inhibition of search distractors when the search stimuli remained in view by the time the probe stimulus was presented (which was taken as evidence for the object-based nature of the inhibitory effect). Further, the inhibition was reduced when distractors underwent a luminance change prior to the probe presentation, an effect, which revealed to be due to reduction in inhibition, rather than to prioritized attentional processing, of the changed distractors. Finally, inhibition of search distractor locations was still evident when eye movements were controlled indicating that the effect was not due to an eye movement artifact.

Chapter 1 - Introduction

1.0 Visual search - basic paradigm and implications

Many tasks in our everyday life involve a process of visual search. For example, we might search for a particular kind of vegetable on a supermarket shelf or for the "my documents" folder on our desktop. Similarly, in a medical practice a dentist often will search in x-rays for caries or other critical information.

In the laboratory, in a standard visual search paradigm, participants look for a *target* item amongst some number of *distractor* items. As it can be seen from Figure 1A, it is relatively easy to find the left-tilted bar amongst vertical bars. The tilted object seems to "pop out" of the display. However, in Figure 1B, observers cannot find the letter T amongst L's until they have serially scanned a number of letters. It seems that some form of additional processing, i.e., *covert shifts of attention*, is necessary in order to detect the target letter.



Figures 1A and 1B. Examples of search displays, usually used in the laboratory. On the left-hand side (1A), the target is the left-tilted bar amongst vertical distractor bars. It seems to 'pop out' of the display, that is, it can be effortlessly segmented from the background distractors. Search in this case is efficient. On the right-hand side (1B), the target is the letter T amongst L distractors, rotated clock-wise at either 0°, 90°, 180°, or 270°. Focal attention has to be deployed serially across the display to find the target. Search in this case is less efficient, that is, the number of display objects strongly affects RT or accuracy.

The total number of items in the display is called the *set size* and on some percentage of trials, usually 50 %, a target is present. On the remaining 50 % of trials, only the distractors are presented. Participants' task is to indicate the presence or absence of a target by pressing either of two keys of a keyboard (or a mouse). The two dependent variables that are commonly studied are reaction time (RT) and accuracy. When RT is the main variable of interest, the displays remain visible until observers respond by pressing a button. RT is generally analyzed as a function of set size, producing two different functions, one for target-present and one for target-absent trials. The functions yielding RT to set-size are used to infer the mechanisms underlying visual search. When accuracy is the main variable of interest, the search stimuli are presented only briefly and are followed by a mask, whose role is to terminate stimulus processing at a given point in time. Accuracy is analyzed as a function of the time interval between the onset of the search stimuli and the mask, which is called *stimulus onset asynchrony* (SOA). The slopes of the accuracy x SOA functions are used to infer the mechanisms underlying search performance.

Returning to Figure 1A, typically search tasks of this type can be executed with short SOAs and with slopes of the RT x set size functions near zero milliseconds (ms) per item. These results were taken as evidence for an underlying *parallel search* process, which assumes that all items can be processed at one time to distinguish the target from the distractor elements. When considering Figure 1B, the search for the 'T' will take longer SOAs and will produce slopes of approximately 20 to 30 ms/item, with target-absent trial slopes of about 40 to 60 ms/item. Search tasks yielding this pattern of results are usually referred to as *serial searches* and the differences between the search rates in target-present and -absent trials are consistent with a *random serial self-terminating search model*. The logic of the model is as follows: In the presence of a target, the target object can be the first or the last item checked by attention, but on average, half of the items have to be checked to detect the target.

When no target is in the display, all items need to be checked by attention to make a target-absent decision, thus yielding to a proportion of 1:2 (target-present : target-absent slopes).
The distinction between parallel and serial processing has a long history (see Bundesen, 1996, for a review) and became theoretically prominent when Anne Treisman proposed her Feature Integration Theory (FIT, Treisman & Gelade, 1980). However, there are several problems with the strong distinction between parallel and serial search made by original FIT (cf. 1.1.1), which led to a revised version of the model assuming no longer a strict dichotomy between serial and parallel processing (Treisman, 1993; Treisman & Sato, 1990). Further, there are models that generally assume that all search items can be processed at once (Broadbent, 1987; Duncan & Humphreys, 1989; Heinke & Humphreys, 2003; Humphreys & Müller, 1993; Ratcliff, 1978; Townsend, 1974) and explicitly rejected the serial/parallel dichotomy, which led Wolfe (1998) to propose the idea of a continuum of search-slopes. In this continuum, visual search is characterized as either ‘efficient’ (search slopes of approximately 0 ms/item; e.g., search for a red target amongst green distractors, Nagy & Sanchez, 1990), ‘quite efficient’ (approximately 5-10 ms/item; e.g., search for a uniquely oriented red target amongst same oriented green and different oriented red distractors, Kristjánsson et al., 2002), ‘less efficient’ (approximately 20-30 ms/item; e.g., search for a rotated T amongst rotated L’s, Horowitz & Wolfe, 1998) or ‘inefficient’ (approximately 30-50ms/item; e.g., search for a red-green target amongst red-blue and green-blue distractors, Wolfe et al., 1990).

1.1 Theories of visual search

1.1.1 Feature Integration Theory

The Feature Integration Theory (Treisman & Gelade, 1980) characterizes visual object perception as a two stage process. In the first ‘preattentive’ stage, the basic perceptual features of objects (e.g., orientation, color) are coded by dimension specific modules operating across the visual field. A spatiotopic activation or feature map is formed by each module, registering its associated value within the feature dimension. Thus, for example for orientation, there may be an individual feature map for vertically oriented objects and another for horizontally oriented ones; for color there will be separate maps for blue and green.

On the second stage spatial attention focuses on an area within a *master map of locations* (which represents where the registered features are without registering their individual values) to retrieve and combine different values represented at that particular location in the respective feature maps. It should be stressed that while feature maps implicitly code feature information, this information can only be represented in an integrated fashion via the master map of locations. This process creates a temporary representation of an object, called an ‘object file’, which can be used to access/interface stored knowledge. This is not the only way in which features can be combined, i.e., spatial attention is not actually necessary. FIT allows that they can be combined according to expected object frames, so that green is linked to grass or blue to the sky (Treisman, 1988). Finally, illusory conjunctions can occur, in which features belonging to different objects are mis-combined, e.g., when there are arbitrary relations between the features of a given stimulus and the stimulus is not attended to.

From FIT it follows that two distinct types of search behavior exist, depending on whether in a visual search display the target is defined by a single feature or by a conjunction of features. In a single feature search, activity from a single feature map will signal the presence of the target enabling the target to be detected rapidly. Treisman and Gelade (1980) presented subjects with a display of colored letters consisting of green X’s and brown T’s. For search for a target differing from the distractors by a single feature, e.g., a blue T or X or S, the number of distractors had no influence, i.e., the function relating RTs to set-size was flat. However, when the target was defined by a conjunction of target features, e.g., a green T, search RT performance was linearly related to the number of distractors presented in the display. The authors suggest that this pattern results from a serial inspection of item locations in the master map, necessary in order to combine the correct features (binding). On such a serial account, the present/absent search slope ratio should be 1:2 as on target present trials, on average only half the total number of display items would have to be processed and, indeed, this is what Treisman and Gelade found.

However, there is conflicting evidence for this claim of FIT showing that all feature searches are not necessarily parallel and that all conjunction searches are not necessarily serial which has led to qualifications of FIT. For example, it was found that search slopes reflect a continuum of difficulty according to their similarity between target and distractors (Treisman & Gormican, 1988; Experiment 1). This was explained by postulating that stimuli activate a number of feature maps, dependent on how close the value of the input feature is to that which the activated feature maps are tuned. The closer the maps are in the feature value to a presented stimulus, the more they will tend to be excited. If they are very close, both features will be activated necessitating the allocation of attentional resources to discriminate the target. It follows that attention deals with ‘clumps’ or groups of items in the display, according to target-distractor similarity (cf. 1.1.3). Similarity is inversely proportional to ‘clumpiness’, so if target and distractors are highly discriminable, the whole set of display items can be clumped. As discriminability decreases, the size of the set of display items to be clumped is reduced accordingly.

Another problem is that many conjunction searches have been found to show shallow or flat search functions, e.g., shape and binocular disparity (Enns & Rensink, 1991; He & Nakayama, 1992; Ramachandran, 1988); color and direction of motion; binocular disparity and color; size, spatial frequency, and contrast (Nakayama & Silverman, 1986); shape and direction of motion (McLeod, Driver, & Crisp, 1988; Kingstone & Bischof, 1999); color and orientation (Wolfe, Cave, & Franzel, 1989; Wang, Kristjánsson, & Nakayama, 2001; Kristjánsson, Wang, & Nakayama, 2002).

Further, it was found that manipulating the number of distractors could affect slopes in a conjunction search (Egeth, Virzi, & Gabart, 1984). A letter/color search task was used with search displays consisting of black O and red N distractors and a red O target. With a 1:1

distractor ratio, search slopes were typical for a conjunction search. However, if the ratio was manipulated and an unequal number of distractors of each type was presented, search was facilitated, indicated by shallower search slopes. It was apparent that search could be restricted to the smaller subset of distractors sharing a target attribute. In the search task mentioned, increasing the number of red N distractors enables search to be restricted to the O distractors only, enabling more efficient search. FIT, however, predicts that serial search is necessary in such conditions.

To account for this contradictory evidence, Treisman and Sato (1990) proposed a revised version of FIT. In particular, revised FIT proposes inhibitory connections between the master map of locations and individual feature maps. If a target is known in advance, feature maps can inhibited actively on the locations map linked with the distractor feature values. For example, if the target is a blue circle amongst green distractors, inhibition from the green feature map to distractor locations reduces the activity of those locations in the master map. Attention is hence directed to the target location. This accounts for the effect on search slopes of the manipulation of distractor ratios as feature maps can be used to inhibit the activity of a subset of distractors. Thus, in the study of Egeth et al. (1984) described above, the N feature map could inhibit activation of the N distractors on the master map of locations resulting in search through only the O items. Master map inhibition could also account for the parallel nature of conjunction searches with highly discriminable features. In this case, inhibition from two feature maps will inhibit target locations leaving the target with the greatest activation.

In order to account for parallel search functions based on 3D features such as line junctions (e.g., Enns & Rensink, 1991), Treisman and Sato (1990) allude the possibility of a limited number of emergent feature detectors. The number of these detectors was necessarily limited due to the combinatorically explosive computational requirements of multi-dimensional feature spaces (Green, 1991), a problem FIT purported to solve by dividing the visual field into uni-dimensional feature representations. However, Treisman and Sato note a previous study of emergent features involving pairs of oriented lines (Treisman & Gormican, 1988), parallel search behavior was not evident.

1.1.2 Guided Search 2.0

Wolfe's Guided Search model (Wolfe, 1994) is similar to FIT in that the visual field is initially decomposed according to certain basic features by parallel pre-attentive processes across the visual field. In contrast to FIT, however, feature maps are computed per dimension rather than for specific feature values within a particular dimension, (that is, they compute a saliency map whose pattern of activation represents the differences in feature values at different locations within that feature module). Saliency maps for each dimension are subsequently weighted and summed (Müller et al., 1995), to form an overall activity or saliency map that plays the same role as the master map of locations in FIT. Attention is guided to the location with the greatest activation and the feature values within this location are conjoined to form a temporary object representation for processing by the object recognition network.

Knowledge of target features can also affect the feature-specific maps in a top down manner. If the target features are known, the coding units representing those features can receive top-down modulatory activation, thus, resulting in a higher overall activation on the dimensional saliency map. Hence, it is more likely that attention will be guided towards the target location under these conditions. Top-down activation is, thus, computed by display item dimension and Wolfe et al. (1990) claim that this necessitates that within-dimension conjunction searches are serial as opposed to between- dimension conjunction searches, which can be parallel provided the display item feature differences are sufficiently marked. For example, a color x color conjunction search will be particularly inefficient (cf. 1.0). A red-green target is very hard to find amongst blue-red and blue-green distractors as activation of red, green, and blue feature values is mediated by the same processing channel. Thus, top-down activation will affect all display items equally. In contrast, for a between-dimension conjunction search, the target will receive the highest activation, as top-down activation is carried independently by both processing channels, respectively.

However, Carrasco, Ponte, Rechea, and Sampedro (1998) showed that within dimension conjunction searches can be efficient if participants are provided with enough practice. In search for a red-green target amongst red-blue and green-blue distractors, target present slopes were reduced from 10 ms/item to 2.3 ms/item in the four blocks of trials. This suggests that dimensional modules can, in fact, provide more than one signal indicating where attention should be guided (Carrasco et al., 1998). Of further relevance, Linnell and Humphreys (2002) showed redundancy gains with within-dimension conjunction targets. Miller's (1982; s.a. Miller and Lopes 1988) inequality test states that the fastest latencies from a two-target display will be no faster than the fastest latencies from a single-target display, if the target items in the two-target display are processed independently (e.g., by a serial search for individual items). As a redundancy gain was found for displays containing two targets as compared to one target (as indexed by faster latencies in the two- relative to the single-target display), Linnell and Humphreys argued that this was consistent with the parallel coding of within-dimensional conjunction targets, with the difficulty of the search task reflecting strong within-dimension grouping rather than limitations on top-down processes.

One further constraint on top-down activation in Guided Search is that it is categorical in nature, i.e., it is limited to a small subset of feature values corresponding to the selection of a single broad-band input channel (Wolfe, 1996). For the orientation dimension, top-down control is constrained to steep, shallow, left, right and tilted by 45°; for color, blue, red, yellow, and green; and for size, big or small.

Finally, when considering conjunction search between dimensions, Guided Search assumes that this can be achieved via target activation rather than distractor inhibition. However, Treisman and Sato (1990) presented data suggesting that top-down processes are mainly inhibitory. In a control condition, search was for a green bar rotated by 27° amongst green and gray bars oriented rotated by 63° and 27°, respectively. In the experimental condition, they added two new distractor types to the original display, green bars at 90° and pink bars at 27°. If top-down processes modulate search efficiency by facilitating activation at the target location, search performance should be unaffected as the two added features are less similar to the target and, hence, should receive less activation from the target feature maps, even perhaps increasing target conspicuity. If, however, inhibition from distractor feature maps constitutes top-down processing, additional distractor feature values will divert inhibitory resources from the feature maps most similar to targets, reducing target conspicuity. Treisman and Sato found that this was the case, search slopes were greater with the addition of other distractor feature values.

1.1.3 Attentional Engagement Theory

Like FIT and Guided Search 2.0, Attentional Engagement Theory (AET; Duncan & Humphreys, 1989; 1992) is a two stage model of visual selection, describing separable pre-attentive and attentive processes, the former working in parallel across the visual field. AET differs fundamentally from the two previously described models in its account of the processing capabilities of the preattentive stage. Rather than postulating attention as necessarily implicated in the binding of features into objects, the output representations of the preattentive stage are featurally complex assemblages termed ‘structural units’. These structural units are hierarchical in that they occur at different spatial scales, for example, compound letter stimuli in which multiple instances of the same individual letter may be arranged so that they form another level, perceived at a higher spatial scale. The highest level of structural unit will be a coarse coded representation of the visual scene. Structural units are segmented according to the principles of similarity grouping. Elements sharing featural properties (e.g., color, shape, and size) at a particular spatial scale will tend to group to form a structural unit. Boundaries between structural units are resolved by discontinuities between these properties. Within the context of visual search, grouping involves not only relations between targets and distractors (T-D similarity), but also between different distractors (D-D similarity). The interaction between these two factors determines search efficiency. When T-D similarity is low, search is efficient irrespective of D-D similarity; when T-D similarity is high, search difficulty is highly dependent on D-D similarity. Hence, rather than making a qualitative distinction between feature and conjunction search, there is a continuum of search efficiency dependent on the strength of grouping between presented stimuli.

In this account, perceptual descriptions are formed at the first stage of visual analysis. Individual groups compete for access to visual short-term memory (VSTM), the latter being equivalent to deployment of attention. Access to VSTM is dependent on the similarity of a perceptual group to a target template. The greater the similarity of a group to a target template the more weight it will be assigned and, hence, the more likely it will enter VSTM. This corresponds to the top-down processing component of the model. As a consequence of the preattentive perceptual grouping defined above, access to VSTM is a process called spreading suppression. The structural integrity of a perceptual group reflects the strength of the linkage between the individual elements of a group. This is reinforced by the distribution of “weight” within a group. If an item within a group is weighted according to its similarity to the target template, the linkage between it and similar items engenders a proportional distribution of that weighting for non-target groups characterizes spreading suppression. From this, it is clear that homogeneous distractors will facilitate their own suppression through weight linkage.

Attentional Engagement Theory provides a good account of the evidence supporting FIT. Take for example, the feature and conjunction searches documented by Treisman and Gelade (1980) as described above. In the conjunction condition, slow search is determined by two factors. Firstly, consider the high similarity between the green T target and brown T and green X distractors, each distractor sharing one target attribute, either the color green or T shape. The target description will enhance the weight not only of the target but also, to a lesser but significant extent, both sets of distractors. In contrast, in the feature condition, the targets' unique attribute, e.g., the color 'blue', ensures that it receives much higher weighting from the attentional template. Note, that the relatively high heterogeneity between the two sets of distractors, which do not share any features, is important for conjunction, but not feature search. In this case, the weight linkage across the total set of distractors is weak, so there is little spreading suppression. However, in the feature search, the high weighting of the target, due to its unique feature value, facilitates rapid access to VSTM.

It seems that revised FIT (Treisman & Sato, 1990; Treisman, 1993) has incorporated some of the ideas proposed by AET. For example, in their Experiment 3, Duncan and Humphreys (1989) showed that an L shape could be found rapidly amongst a distractor set of L's, rotated 90° clockwise or anti-clockwise provided these distractors were homogeneous. However, when both clockwise and anti-clockwise rotated L's were present in the display, search was difficult indicating that increasing distractor dissimilarity can effect search performance. In the case of homogeneous L distractors, FIT proposes top-down modulable connections between the master map of locations and individual (orientation) feature maps (cf. 1.1.1) that can inhibit the L shape. However, to account for the latter finding, FIT assumes the inhibitory connections between the master map and the individually orientation maps to become less efficient when D-D dissimilarity increases.

1.2 Memory in visual search

1.2.1 Overview

Models of visual search incorporate a target description that can provide positive guidance to the target in a top-down manner. However, theorists (e.g., Duncan & Humphreys, 1989; Treisman & Sato, 1990; Wolfe, 1994) are not explicit about the type or the role that top-down guidance plays in visual search. In a recent review, Shore and Klein (2000) argued that memory in visual search is organized around three different time scales (see Figure 2).

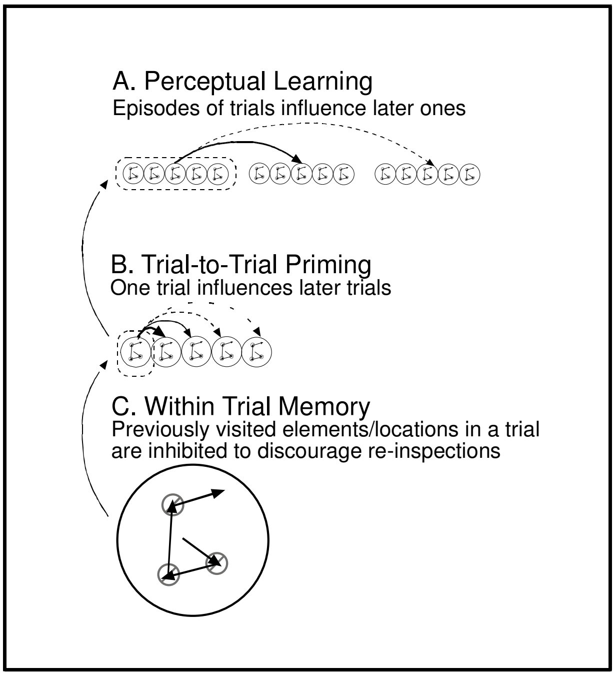


Figure 2. The contribution of memory on search behavior on various time scales. (A) On the broadest time scale, episodes of trials can influence later ones, an effect which can be observed for hours to years and is referred to perceptual learning. (B) On the shallower time scale, a single trial can leave an imprint on the next trial(s), a phenomenon which can be observed for seconds to hours and is referred to trial-to-trial priming. (C) Within-trial tagging of previously visited elements/locations can be observed for milliseconds to seconds and it reduces the likelihood of re-examining items. Several mechanisms have been suggested to account for this memory, for example, inhibition of return, attentional prioritization of new items, or visual marking (adapted from Shore and Klein, 2000).

The first time scale involves perceptual learning across blocks of trials. The second time scale involves trial-to-trial priming across single trials, and the last time scale involves the memory, which prevents participants from re-inspecting already visited elements/locations within a single trial.

1.2.2 Perceptual learning

The term perceptual learning refers to implicit learning of contingencies over a number of trials, which can have long-term effects (hours to years) on the speed of visual search. The contingencies that are implicitly learned can be task-specific (e.g., Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977), target-specific (Ahissar & Hochstein, 1997), distractor-specific (Lubow & Kaplan, 1997; Flowers & Smith, 1998) or context-specific (Chun & Jiang, 1998; 1999; 2003; Chun & Phelbs, 1999; Jiang & Chun, 2001; 2003; Olson & Chun, 2001; 2002). Evidence for perceptual learning in search paradigms usually comes from a comparison of consistent mapping (CM) and variable mapping (VM) conditions (e.g., Schneider & Shiffrin, 1977; Chun & Jiang, 1998). In consistent mappings, the identities of target and distractors remain constant over blocks of trials, whereas in VM conditions either the target or distractors changes identity between trials. The key observation is that search performance in the CM condition is consistently superior to that in the VM condition, which is taken as evidence for a memory aiding performance in the CM condition.

1.2.3 Trial-to-trial priming

When a trial sets up a memory trace and influences the next trial(s), this effect is usually referred to trial-to-trial priming. Recent work by Maljkovic and Nakayama (1994; 1996; 2000; McPeek et al., 1999) showed that target and distractor features (color, spatial frequency, spatial location) can affect subsequent performance when these attributes are repeated. In a series of experiments (Maljkovic & Nakayama, 1994), the target was defined as the odd colored element in a display of three elements either a red diamond amongst green diamonds (or vice-versa). Participants were instructed to respond to the shape of the singleton color target, with either one side or the other (i.e., left or right) of the diamond elements having been cut-off. It was found that repetition of the target color facilitated responses (the effects were in a range of 30 to 110 ms, dependent on the observer). In contrast, repetition of the target shape, and as a result, repetition of the target response, had only minimal effects.

Further, this carry-over effect from repeated color targets was shown not to be affected by observers' expectations. In Experiment 4, the authors showed that, even if participants knew the identity of the target, repetition of the attention-driving or target feature primed responses. Further, when participants were asked for the target defining feature (e.g., color, response), their performance was only at chance level (Maljkovic & Nakayama, 2000; Experiments 1 & 2). In a follow up study, Maljkovic and Nakayama (1996) showed a similar priming effect when the location of the target was repeated. They concluded that the mechanism responsible for both featural or positional facilitation was a passive (implicit) memory system.

It is part of a debate whether these memory effects are top-down modulable. For example, Müller, Reimann, and Krummenacher (2003) found evidence that dimension-specific priming can be modulated by top-down control. When observers were informed by a symbolic pre-cue in which dimension (color, orientation) the target was likely to be defined (i.e., trial-wise rather than block-wise cueing procedure), dimension-specific intertrial effects were reduced for valid an invalid trials relative to a neutral condition. Interestingly, there remained a residual intertrial transition effect, even with 100% valid pre-cues, which was interpreted in such a way that top-down influences cannot be completely overcome automatic priming. Further, when participants were asked for the target defining dimension or feature on some proportion of trials, dimension-specific intertrial effects were increased relative to a no-memory condition, in which participants never were asked for the target defining dimension or feature (Müller, Krummenacher & Heller, 2004). Although automatic priming was sufficient to produce facilitation in the no-memory condition, the increase in the amount of intertrial facilitation was interpreted in favor of a top-down modulable memory effect, namely the necessity to actively encode the target dimension or feature.

Probably, these differing results suggest independent priming mechanisms, one at the feature level (e.g., Maljkovic & Nakayama, 1994), which is top-down impenetrable and one at the dimensional level (e.g., Müller, Krummenacher, & Heller, 2004) which is sensitive to top-down biasing. However, the results of Hillstrom (2000) give rise to another explanation. In a series of experiments, she manipulated the relative salience of the target selection feature. In Experiment 1, participants responded to the shape for a color-singleton target, which changed its color either predictably (i.e., every two trials) or randomly in consecutive trials. The results were similar to those reported by Maljkovic and Nakayama (1994, Experiment 4), in that a RT advantage was found when the color of the target was repeated on consecutive trials. Interestingly, the search RTs were overall faster, by 115 ms, when the target color changed predictably rather than randomly across trials, a finding interpreted by Hillstrom (2000, p. 803) as an effect of (top-down) “expectancy” – at variance with Maljkovic and Nakayama (1994).

Further, a similar pattern of effects was found when participants were prevented from operating a simple saliency-based search strategy, that is, if an additional color-singleton necessitated feature search and participants had to set themselves on a trial-by-trial basis for a particular feature (Experiment 3), or when they had to set themselves for a particular conjunction of target features (Experiment 4), requiring a template-based search strategy (cf. Duncan & Humphreys, 1989). Hillstrom took the findings from a variety of search tasks (from singleton feature search to cued feature and conjunction search) to suggest that a single memory mechanism may be responsible for these effects. Interestingly, in the conjunction search task (Experiment 4), repetition did not affect the search time per element (the slope of the search RT/display size function), but rather the base RT (y-intercept of the function). Hillstrom (p. 811) took this to suggest that repetition affects the speed of the spatially parallel enhancement (in Hillstrom’s terms, “prioritizing”) of target feature coding (cf. Wolfe, 1994).

Therefore, Hillstrom (2000) proposed an episodic memory mechanism for prioritization. The idea of the mechanism is as follows: If the display features that are used to make attentional selection will be repeated, a memory trace of the priorities assigned to the display items in the previous trial can be used to prioritize the new display items. In contrast, if the search features changed, a new set of display priorities is set up, leading to RT costs.

However, the spatially parallel enhancement of target coding features must not be the only way to explain Hillstrom's findings. For example, Kristjánsson, Wang, and Nakayama, (2002; Wang, Kristjánsson, and Nakayama, 2001) assume expedited grouping of search distractors to account for facilitatory priming. In particular, Kristjánsson et al. suggest facilitatory priming to be due to faster perceptual grouping of same defined distractors, which, in turn, might lead to faster target-present, as well as -absent, decisions – due to faster discernment of target presence against the background of homogeneous, grouped distractors. Evidence for their proposal derives from a conjunction search task, where the authors found facilitatory priming on target-present and -absent trials (i.e., in the latter case even in the absence of any target stimulus). Nevertheless, it is important to note that on target-present trials, Kristjánsson et al. have also considered the possibility that facilitatory priming might result from the repetition of the target features alone (cf. Maljkovic & Nakayama, 1994; Experiment 8).

It is a question of interest, what level of representation is primed by repeated target and distractor features. The results of Maljkovic and Nakayama (1996; Experiment 3) suggest that it is the object and not its retinal position that is primed by repeated targets. To a similar conclusion came McCarley and He (2001), who investigated priming in 3-D organization task. When search displays were followed by a brief mask (Experiment 2), priming of 3-D perceptual organization appeared to be unaffected by the post-stimulus mask, suggesting that facilitatory priming, enacted by the repetition of stimulus features, resulted 'from the persistence of attentional weights and not from the persistence of a sensory representation itself' (p. 200).

It seems that there is an agreement that trial-to-trial priming does not result from the persistence of low-level sensory stimulation. However, recent findings (e.g., Cohen & Magen, 1999; Cohen & Shoup, 1997; Found & Müller, 1996; Müller, Heller, & Ziegler, 1995) led to the debate whether priming arises at a (later) perceptual or at a response stage of visual processing. According to the 'dimension-weighting account' (Müller et al., 1995), focal attention operates on a master map of integrated saliency signals derived separately in dimension specific (perceptual) modules. Prior to the detection of the target, its dimension must be attentionally weighted, a process which is time consuming. So when the dimension of the target is repeated between trials, facilitatory priming occurs because the target dimension is even weighted, permitting rapid search. In contrast, Cohen and Shoup (1997) introduced the 'cross-dimensional response selection model', in which there is no single response selection mechanism, but one for each dimension module. The authors assume that there exist visual dimensional modules with separate perceptual processes. However, they also assume that after visual selection, the response assignments to single features are determined separately and independently within each dimension module. So according to the model, RT benefits in visual search occur because of the priming of the relevant response module and not the perceptual (dimension) module. However, there are psychophysical findings that provide evidence for the former account (e.g., Krummenacher, Müller, & Heller, 2002a; 2002b) or the latter account (e.g. Cohen & Magen, 1999) and sometimes it appears that the question of the priming locus is answered from those who give the best arguments and not empirical findings (Müller, personal communication). Although a debate, findings from PET- (Corbetta et al., 1991) or fMRI-studies (Pollmann et al., 2000; Weidner et al., 2002) make it highly probable that it is the stage of perception rather than the stage of response that is primed by repeated search items.

1.2.4 Within-trial memory

When participants are involved in a search task, they show no (or only few) re-inspections of search elements/locations in a given trial. Usually, it is assumed that a 'memory' in the trial prevents participants from re-inspecting elements/locations. There are several potential candidates that could account for within-trial memory:

- inhibition of return (e.g., Posner & Cohen, 1984),
- attentional prioritization of 'new objects' (e.g., Yantis & Johnson, 1990),
- visual marking (e.g., Watson & Humphreys, 1997).

Inhibition of return. Posner and Cohen (1984) first showed the phenomenon dubbed inhibition of return (IOR). They found that a peripheral (exogenous) cueing stimulus showed attentional enhancement of target detection if the cue-target SOA was less than 300 ms. After 300 ms, target processing was inhibited and Klein (1988) supposed that this may be one way that the attentional system keeps track of items in serial visual search. Klein used a probe-dot paradigm to investigate attentional processing at distractor locations in a conjunction search condition. Probe-dot detection was worse at distractor locations than at blank locations consistent with inhibitory tagging of distractors, the tagging presumed to make it less likely that attention would be guided back to previously examined items. Importantly, there was no difference between the distractor and blank locations in a feature search condition, discounting a forward masking account.

However, Wolfe and Pokorny (1990) and Klein himself (Klein & Taylor, 1994) failed to replicate this effect. Takeda and Yagi (2000) noted that previous research implicated object-based attention in IOR (e.g., Tipper, Driver, & Weaver, 1991). They reasoned that since the search items offset before the probe-dot onset, this might have removed inhibitory tags applied to object level representations. To test this prediction, they presented C and O stimuli. In the easy search condition, participants searched for a C amongst O's and in the difficult search condition an O amongst C's (Treisman & Gormican, 1988). The probe-dot appeared within the display, i.e., the latter did not offset simultaneous with the presentation of the probe-dot. A probe-dot RT cost was found at distractor locations in the difficult search condition in comparison with the easy search condition, replicating Klein's (1988) original result.

Further, Müller and von Mühlenen (2000) showed that the disadvantage for on-probes (relative to off-probes) in serial (relative to parallel) search was replicable only under specific conditions, that is: only when (1) the search display remained visible when presenting the luminance increment probe (Experiment 3) and (2) probes appeared equally likely at search array and empty locations (Experiment 4). Their major conclusion was that IOR in serial visual search is dependent on the search array stimuli (or critical parts of them) remaining in the display at the time the detection-probe is presented.

Horowitz and Wolfe (1998) have generally questioned the hypothesis that memory processes, keeping track of visited locations, are necessary in serial visual search. They used two kinds of search display in serial search for T amongst L's. Firstly, a dynamic condition, in which the target and distractors changed positions randomly every 111 ms. Secondly, a standard static visual search display, which was used as a baseline condition. Monte Carlo simulations of a serial sampling model showed that if previously visited locations had to be re-sampled, search slopes should be twice as steep in comparison with those in the static condition. Strikingly, the authors found no difference in the search slopes between the dynamic and the static displays, implying that there is no role for a memory system which checks tagged location. Although an attractively strong claim, it subsequently became a controversial issue (e.g., pro memory: Gibson, Lee, Skow, Brown, & Cooke, 2000; Gilchrist & Harvey, 2000; Klein & McInnes, 1999; Kristjánsson, 2000; Peterson, Kramer, Wang, Irwin, & McCarley, 2001; McCarley, Wang, Kramer, Irwin, & Peterson, 2003; Shore &

Klein, 2000; von Mühlenen, Müller, & Müller, 2003; contra memory: Horowitz & Wolfe, 2001; 2003; Woodman, Vogel, & Luck, 2001). For example, Shore and Klein (2000) re-analyzed the complete data set of Horowitz and Wolfe (1998), including the target-absent trials. The authors found differences between the dynamic and the static condition in several performance parameters (e.g., slopes; base RTs, that is, the y-intercepts of the RT x set-size function, rate of false alarms, and standard deviation), indicating different processes in the two search conditions. They concluded from those dissimilarities that Horowitz and Wolfe's findings provide no good reasons to argue that visual search is memory-less. Further, when participants were engaged in a dynamic condition in which they viewed the display through an aperture making only a limited region of the display visible (the aperture condition), no differences in performance were revealed between the dynamic and aperture conditions (von Mühlenen, Müller, & Müller, 2003). This led the authors to assume that in the dynamic condition (as well as the aperture condition), participants used a sit-and-wait strategy (Eriksen & St. James, 1986), 'directing focal attention to a whole group of locations and waiting there for the target to appear' (von Mühlenen, Müller, & Müller, 2003; p. 314).

Attentional prioritization of new objects. Yantis and Johnson (1990; Yantis & Jonides, 1984; Jonides & Yantis, 1988; Yantis & Hillstrom, 1994) proposed that the visual-attention-memory system can prioritize processing for up to four items marked by (simultaneous) abrupt visual onsets. The evidence for this account came from a serial visual search study in which the ratio of abrupt-onset to no-onset items was systematically varied (Yantis & Johnson, 1990). It was found that (i) the search RTs were, on average, faster for abrupt-onset items than for no-onset items; (ii) for onset targets, the function relating search RT to the number of abrupt-onset items at first exhibited a shallow increase up to four items, while the function for no-onset items showed a steep increase; (iii) thereafter, the two functions exhibited equivalent increases. This pattern is as predicted if the attentional system has a limited number of four priority tags available. In sum, according to the this account, the appearance of a new perceptual (onset) object has important consequences for the deployment of attention. The visual system seems to be predisposed to attend to a new object representation.

Visual marking. Visual marking is a top-down mechanism, thought to facilitate the selection of new objects in the visual field (Watson & Humphreys, 1997), via the attentional suppression of old items. In their initial study, participants searched for a conjunction target, a blue H amongst blue A's and green H's. There were three conditions. Firstly, a standard conjunction search in which participants made a present/absent judgment for the blue H target. In the second, the blue H target appeared solely with the blue A's, constituting a relatively easy feature search condition. In the preview condition, items in the search display were temporally separated. Following the presentation of the fixation cross, a preview display of green H's appeared. After 1,000 ms, the target and the blue A distractors were added on present trials, or just the blue A's on absent trials. Participants were informed that the target - if present - would always appear with the second set of distractors. The result of this experiment showed that participants were able to detect the target in the preview condition as efficiently as in the feature search condition, i.e., significantly faster than the standard conjunction condition. It seems that when the search display was presented over time, participants were apparently able to successfully curb any influence of the green H distractors on search through the items appearing after the 1,000 ms preview period. Other results have confirmed this preview advantage for a variety of conjunction and letter search stimuli (Theeuwes, Kramer, & Atchley, 1998; Olivers et al., 1999).

Watson and Humphreys (1997) proposed an inhibitory memory (template) that mediates the attentional suppression of the old search items. In Experiment 8, they showed that the preview benefit requires attentional resources. When participants were presented with a concurrent central load task, in this case verbally pronouncing a stream of centrally presented digits, simultaneously with the old distractors, no RT benefit was found in the preview condition as compared to the conjunction baseline. Further work by Olivers and Humphreys (2002) has shown that if the presentation of the preview distractors occurs within the attentional blink (Raymond, Shapiro, & Arne, 1992), the marking process is disrupted consistent again with a top-down applied attentional resource.

There is conflicting evidence whether other attentional mechanisms could be responsible for the preview benefit. In their Experiment 5, Watson and Humphreys (1997) countered the idea that the participants were merely prioritizing abrupt onset items (see above), by producing local luminance decrements in the preview items occur simultaneously to the presentation of the new items. They argued that, if the onset of the new items was solely responsible for the preview advantage, then the luminance decrement in the old items should make no difference. Again, search in this modified preview condition was not better than in the conjunction baseline, indicating the preview benefit to be due to the inhibition of the old distractors (green H's). However, as Donk and Theeuwes (2001) pointed out, further studies offer an alternative explanation, in that it has shown that offset stimuli can moderate the prioritization of onset stimuli (e.g., Martin-Emerson & Kramer, 1997). Donk et al. investigated the abrupt onset account by independently manipulating the 'degree of onset' of the preview and onset stimuli. In Experiment 1, participants performed a difficult letter search task (as in Theeuwes et al., 1998) with the display items being equiluminant with the background. The design of the experiment differed from that of Watson and Humphreys (1997) in that rather than comparing the preview search condition with a conjunction and feature search baseline, the number of old vs. new items was systematically manipulated. Successful visual marking was commensurate with search slopes being independent of the number of old items, i.e., if RTs increase as a function of the number of new items. The results of Experiment 1 showed that for stimuli equiluminant with the background, search performance varied with the number of new and old items. In contrast, in Experiment 3, in which only the old items were equiluminant with the background, search slopes were independent of the number of old items. Donk et al. concluded that the visual marking effect required that the new items onset with a luminance increase, i.e., that the inhibition of the old items hypothesis could not be supported in this case.

In a contrasting finding, Watson and Humphreys (2000) provided evidence to support an inhibitory process, using a probe-dot paradigm. When using the same conjunction stimuli as described above, Experiment 1 assessed the accuracy of probe detection at old item locations with that of the new item locations in preview trials. In addition, probe-dot accuracy was measured for the different distractor types, green H's and blue A's, in the standard conjunction baseline condition. The bulk of the trials in the conjunction and preview conditions were standard search trials. On the remaining trials, a tone indicated to participants to detect the presence or absence of a probe dot appearing within the distractors. In the preview trials, it was found that participants were significantly worse detecting probe dots appearing within the old green H's than the new blue A's. Moreover, this performance decrement for probes appearing within green H items, was not apparent in the standard conjunction search condition, supporting the notion that inhibition is applied to the old items in preview displays.

1.4 Summary of Introduction

In the visual search paradigm, the main independent variable is set size - the number of objects in the display - and the main dependent variable is a measure of efficiency, i.e., the extent to which reaction time or accuracy or both are affected by variations in the number of objects in the display. Participants are instructed to search through a presented display, containing a restricted set of visual features, for a specific target, for example a left-tilted bar amongst vertical bars. If search is efficient, such as in conditions as just mentioned, RTs and accuracy are largely unaffected by set-size, i.e., the target is effortlessly segmented from the background distractors. If search is less efficient, RTs and accuracy are strongly affected by set-size, i.e., focal attention has to be deployed across the display enabling 'narrow band' discriminations over a limited area. Feature Integration Theory and Guided Search 2.0 assume that efficient search is done in parallel and less efficient search is done serially. Attentional Engagement Theory proposes no capacity limitations in visual search and interprets search efficiency in terms of the impact of discriminability on a parallel decision process. Further, there is evidence that facilitatory and inhibitory memory mechanisms operate in visual search to decrease the influence of items that have already been identified as not relevant to subsequent search (IOR, attentional capture of onset items, visual marking) or to prioritize selection for stimuli that have been attended in previous trials (trial-to-trial priming) or previous blocks of trials (perceptual learning).

1.5 Overview of Thesis

This thesis examines the role of inhibitory and facilitatory short-term memory mechanisms in the guidance of visual search. More specifically, it attempts to assess the respective contributions of trial-to-trial priming to search behavior under feature and conjunction search conditions. Further, it attempts to access the contribution of within-trial memory to search behavior under feature search conditions. Chapters 2 and 3 investigate the role of trial-to-trial priming in feature and conjunction search, respectively. In Chapter 4, the contribution of an inhibitory short-term memory mechanism, similar to visual marking, to search for singleton feature targets, is investigated.

As discussed above, previous work (Maljkovic & Nakayama, 1996) has shown that the repetition of target positions systematically influences detection performance across sequences of trials: When the target position was repeated, there was facilitation; when the target changed its position to that of a distractor on a previous trial, there was inhibition. Positions adjacent to previous targets and distractors also showed facilitation and inhibition, respectively, though of reduced magnitude. These effects, which were evident across sequences of five to eight trials, were interpreted as reflecting an implicit short-term memory for the guidance of visual search, which is graded in both space and time.

In Chapter 2, the capacity of the memory system underlying positional facilitation and inhibition is investigated. In Experiment 1, participants responded to the orientation of a color singleton target, which was presented amongst a variable number of distractors (i.e., either 3-, 4-, 6-, or 8-element displays; block-wise rather than trial-wise manipulation). The color, orientation, and position of the singleton target and distractors changed randomly from trial to trial. Importantly, although target and distractor positions changed randomly in consecutive trials, in Experiment 1, the positions of the search elements were always equidistant of each other. The results showed that facilitation of a previous target location revealed to be independent of the number of distractors. However, inhibition of previous distractor locations was hardly dependent on the number of search distractors and was evident only in the case of two distractors, suggesting the memory responsible for priming of positions to be capacity-limited to three (one target and two distractors) locations. Further, the dissociation between facilitation and inhibition was taken as evidence that the memory consists of two distinct components, one responsible for target and one responsible for distractor locations. In Experiment 2, the number of display elements remained constant (i.e., 3-element display in Experiment 1). Again, the color, orientation, and position of the target and distractors changed randomly between trials. But in contrast to Experiment 1, the distances between target and distractors locations changed randomly in consecutive trials. By this manipulation, no evidence for facilitation and inhibition of locations was found indicating priming of positions to be dependent on stimulus arrangement in sequences of trials.

Chapter 3 investigates the mechanisms of cross-trial priming in conjunctive visual search, that is, whether the RT advantage for the repetition of same defined search elements results from the repetition of target or distractor features (Kristjánsson, Wang, & Nakayama, 2002). In a series of experiments, participants' task was to detect the uniquely oriented red target, which was presented amongst differently oriented red and equally oriented green distractors (i.e., color x orientation conjunction). To access the mechanisms of cross-trial priming, the number of target orientation alternatives was unequal to the number of red distractor alternatives. In Experiment 1A, the number of red distractor alternatives exceeded the number of target alternatives (distractor uncertainty). There were 2 red target (horizontal, vertical), 2 green (horizontal, vertical) and 4 red distractor alternatives (horizontal, vertical, and diagonal, i.e., all left- or right-oblique by 45°, respectively), allowing the orientation of the target to be repeated independently from the orientation of the red distractors (i.e., red-horizontal target amongst green-horizontal and red-diagonal distractors followed by red-horizontal target amongst green-horizontal and red-vertical distractors). In Experiment 1B, there were 4 red target, 2 green and 2 red distractor alternatives (target uncertainty).

The results of Experiments 1A and 1B were similar. On target-present trials, RTs were significantly faster when the orientation of the target, together with the orientation of the red distractors, was repeated, relative to the non-repetition of target and red distractor orientation. However, this facilitatory effect did not distinguish from the effect when only the orientation of the red distractors, without the target orientation, was repeated. Further, the facilitatory effect resulting from the repetition of the target, without the red distractor orientation, was only small in magnitude. In addition, a reliable facilitatory effect was also found on target-absent trials, when the orientation of the red distractors was repeated. The pattern of results was taken as evidence that cross-trial priming results mainly from the repetition of the same oriented red distractors. Interestingly, although the uncertainty associated with a possible distractor (Experiment 1A) or target orientation (Experiment 1B) did not produce a reliable effect, the RT advantage tended to be larger, when distractor uncertainty was high (Experiment 1A).

Support for the assumption that facilitatory priming results mainly from the repetition of same oriented red distractors was found in Experiment 2, where there were 2 red target, 4 green and 2 red distractor alternatives. Contrary to Experiments 1A and 1B, in Experiment 2 the orientation of the green distractors was no more coupled to the orientation of the red target, that is, the green distractor orientation could be repeated independently of the target orientation. It was expected that if the facilitation in Experiment 1A and 1B resulted from the repetition of the red distractors, then the repetition of the green distractors should produce no facilitatory priming. And that is exactly what Experiment 2 found: No evidence for a facilitatory effect when the orientation of the green distractors, rather than the red distractors orientation, was repeated in consecutive trials.

In Chapter 4, a probe-dot technique (Klein, 1988) was used to access inhibitory memory mechanisms in a singleton feature task. As noted earlier, Müller and von Mühlenen (2000) observed relatively large RT differences between on-probe and off-probe RTs in a serial relative to a parallel search task, which was taken as evidence for IOR operating in (serial) visual search. As of interest here, on-probe costs were relatively large, even on target-absent trials in the parallel search task. To examine whether such on-probe RT costs are entirely attributable to forward masking by the search stimulus on the subsequently presented on-probe, Experiment 1 compared probe detection performance in a parallel search task with a passive-viewing task, in which participants were instructed to only passively view, rather than actively search, the display. There were three main display conditions: the search display stimuli were extinguished prior to the presentation of the probe-dot (display-off); only the internal corner junctions of the search stimuli were extinguished (part-off); or the search stimuli remained visible until the observer had responded to the probe-dot (display-on). The results showed that on-probe costs were reduced in the passive viewing condition, which provided a measure of forward masking, relative to the parallel search task indicating that processes other than forward masking must have increased the on-probe costs under active search conditions. In Experiment 2, participants' eye movements were monitored to rule out that the increased on-probe costs in the parallel search task of Experiment 1 were caused by eye movements during the search process. Experiment 2 found evidence for reduced, but significant on-probe RT costs in the parallel search condition relative to the passive-viewing condition, suggesting this inhibitory effect not to be due to participants' eye movements. Finally, in Experiment 3, the nature of the inhibition of search distractors was further investigated. Experiment 1 showed reduced on-probe RT costs in the part-off condition relative to the display-on condition, an effect which could either be due to the attentional prioritization of changed distractors (Yantis & Jonides, 1984), or the reduction in the inhibition associated with them. However, since in the part-off condition of Experiment 1 all stimulus changes were global, i.e., the removal of the internal corner junctions appeared at all stimulus locations, Experiment 1 could not distinguish between the attentional prioritization account or reduced inhibition account. Therefore, in Experiment 3, the proportion of changed to unchanged search distractors was manipulated. If attentional prioritization was due to the reduced on-probe costs for changed relative to unchanged distractors, the reduced inhibition was expected to be dependent on the number of changed distractors (Yantis & Johnson, 1990). In contrast, if luminance changes decrease the inhibition associated with search distractors, the reduced on-probe RT costs were expected to be independent of the distractor manipulation, that is, affecting all changed distractors equally and simultaneously. Experiment 3 found distractor inhibition to be unaffected by the number of changed distractors, supporting the reduced inhibition account rather than the attentional prioritization account.

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Chapter 2 – Cross-trial priming of element positions in pop-out visual search: Limited in capacity and dependent on stimulus arrangement

Abstract

Two experiments examined cross-trial positional priming (Maljkovic & Nakayama, 1994, 1996, 2000) in visual search. Experiment 1 tested the positional capacity of priming (with regularly arranged target and distractor elements). When the target appeared at a previous target location, response times (RTs) were reduced (facilitation relative to neutral baseline); when the target appeared at a previous distractor location, RTs were slowed (inhibition). In contrast to the facilitation, the inhibition was revealed to be dependent on display size, suggesting the capacity of priming to be limited to three elements/locations (target plus 2 distractors, arranged in an equi-lateral triangle configuration). Experiment 2 revealed little facilitatory and no inhibitory effects with 3-element displays when the elements' spatial arrangement was made unpredictable. This indicates that positional (in particular, inhibitory) priming critically depends on the configuration (regularity, simplicity) of the display elements across sequences of trials. These results are discussed with respect to the spatial capacity of cross-trial priming and the role of the search context for priming in visual search.

Introduction

Implicit short-term memory in visual search

For detecting a target amongst a set of distractors, it may be considered important to know how the target differs from the distractor elements. For example, the target definition may need to be explicitly represented in working memory, in order to provide criteria for when the search is to be terminated (e.g., Treisman & Gelade, 1980; Treisman & Sato, 1990).

However, recent work by Maljkovic and Nakayama (1994, 1996, 2000; McPeek, Maljkovic, & Nakayama, 1999) has demonstrated the automatic or implicit nature of the memory underlying visual search performance. In their experiments, participants responded to the orientation of a color singleton target, which was either defined as a single red object amongst two green distractors or a single green object amongst two red distractors, presented on the circumference of an imaginary ellipse around central fixation (i.e., essentially a '*pop-out*' search task, despite target detection being based on a target feature different from that determining the response). The color and position (as well as the orientation) of the target and, consequently, of the distractors changed unpredictably from trial to trial (however, the spatial arrangement of the three elements in terms of a near equilateral triangle remained the same). As a main result, observers identified the target's orientation faster when the color or the position of the singleton target on the previous trial(s) was repeated compared to when it was changed. Interestingly, when observers were asked to indicate the target- or, respectively, response-defining features on preceding trials (i.e., color, position, or, respectively, orientation; Maljkovic & Nakayama, 2000, Experiments 1 and 2), their performance was at chance levels. Moreover, even when the defining color of the target switched predictably between pairs of trials and observers could thus anticipate a color change, there was still an undiminished effect of the target-defining color on the previous trial (Maljkovic & Nakayama, 1994, Experiment 4; but see Hillstrom, 2000, for discrepant results). Maljkovic and

Nakayama concluded that the repetition effects were not subject to voluntary control, but rather reflected a automatic and implicit short-term memory for the guidance of visual search.

There is an ongoing controversy whether these and related repetition effects in visual search are simply due to passive and automatic processes that are not top-down penetrable, or whether a degree of top-down modulation is possible (e.g. Hillstrom, 2000; McCarley & He, 2001; Müller, Krummenacher & Heller, 2004; Müller, Reimann & Krummenacher, 2003). For example, Hillstrom (2000) found similar facilitatory and inhibitory effects as described by Maljkovic and Nakayama (1994) when presenting two different color singletons in a feature and, respectively, a conjunction search task (Experiments 3 and 4, respectively). In the feature search task, each display contained two color singletons and the (response-relevant) target singleton on a given trial was pre-specified by an auditory cue. In the conjunction task, each display also contained two unique elements (a solid pink and a textured purple element, amongst solid purple und textured pink elements), and which one of the two unique elements was the response-relevant was pre-indicated by an auditory cue. The experiments were run in trial sequences in which the target definition changed either randomly from one trial to the next (random sequence) or in regular (AABBAA…) alternations (alternating sequence). The main findings were that, although there was RT facilitation when the target definition was repeated rather than changed, there was no advantage in performance for alternating as compared to random sequences. The latter is in contrast to Hillstrom’s Experiment 1, in which, in the absence of a pre-cue to the target on a given trial, there was a large advantage for alternating trial sequences – which Hillstrom interpreted as an effect of top-down “expectancy” (p. 803). Hillstrom argued that, in her Experiments 3 and 4, the tasks required a memory representation of target (definition) set up in response to the pre-cue, which influenced target selection in a top-down manner, abolishing the normal disadvantage for random as compared to alternating trial sequences.

Similarly, Müller, Reimann, and Krummenacher (2003) reported evidence that dimension-specific priming (e.g., Found & Müller, 1996) can be modulated by top-down control. When observers were informed by a symbolic pre-cue in which dimension (color or orientation) a singleton feature target was likely to be defined on a given trial (i.e., trial-wise cueing procedure), dimension-specific cross-trial transition effects (repetition vs. change of target-defining dimension) were reduced for valid- and invalid-cue trials relative to a neutral-cue condition. Importantly, there remained a residual transition effect even with 100 % valid pre-cues, which was taken as evidence that top-down influences cannot completely overcome automatic priming (which may last for several seconds; e.g., Majkovic & Nakayama, 2000; Experiment 3). Furthermore, Müller, Krummenacher, and Heller (2004) reported that, when observers were asked to report for the defining feature or, respectively, dimension of the singleton target on some proportion of trials, the dimension-specific cross-trial transition effects were increased relative to a condition in which observers never had to (explicitly) encode the defining feature or dimension of the target. Müller et al. interpreted this finding in terms of top-down modulation of (largely automatic) priming, resulting from the necessity to actively encode the target feature or dimension.

In contrast, McCarley and He (2001), who examined observers’ performance in 3-D perceptual-organization tasks, found no evidence for voluntary control of priming. In their Experiment 4, the 3-D orientation of the search stimuli was pre-specified trial-wise by an auditory cue, to force participants to use a top-down strategy. However, similar to the results of Maljkovic and Nakayama (1994), the predictability of the surface orientation did not overcome automatic priming, that is: there was still a RT advantage when the 3-D orientation of the search stimuli was repeated rather than changed.

Characteristics of spatial visual short-term memory

Maljkovic and Nakayama (1996) reported evidence that priming is not simply "bound" to the exact target and distractor locations in the search display. They observed facilitatory priming not only for the target location, but also for positions adjacent to the target on previous trials; and inhibitory priming not only for the locations of distractors, but also for positions adjacent to distractors on previous trials. Maljkovic and Nakayama concluded that positional priming effects exhibit some spatial spread around the target and distractor locations.

Since there was always one target and two distractors in Maljkovic and Nakayama's experiments, their results would suggest a priming capacity of at least three display elements/locations (1 target plus 2 distractors). Although there is evidence for a distinction between trial-to-trial priming and single-trial memory on the basis of their temporal characteristics (Shore & Klein, 2000), there is no good reason to separate 'within-' and 'across-trial' memory with respect to their spatial characteristics. [Note that 'within-trial memory' subsumes conditions in which a single trial consists of two temporally separated display frames that need to be compared. Despite this, the memory to be retained of the first frame for comparison with the second frame can be discarded once the response has been made. In this sense, one can refer to this as a 'within-trial' memory.]

With regard to the spatial capacity of visual short-term memory (VSTM), there is a broad range of findings from studies that have investigated observers' performance within single experimental trials. For example, in the study of Phillips (1974), observers had to compare two successively presented random dot patterns with regard to whether they were the same or different. The dot patterns varied in (cell matrix) size and were displayed with varying inter-stimulus interval (ISIs). Phillips found that, while performance was little affected by ISI, the effect of size was significant when 8 x 8 (6 x 6, and 5 x 5) matrix dot patterns cells were compared against 4 x 4 patterns. He concluded that VSTM was limited in capacity to 4 x 4 dot patterns. More precisely, the fact that only half of the cells were occupied in 4 x 4 matrices (i.e., 8 dots) would suggest a VSTM capacity of eight elements/locations.

A similar technique was used by Luck and Vogel (1997; Vogel, Woodman, & Luck, 2001). In a series of experiments, they found evidence for a VSTM capacity of four elements\locations. In one experiment, the capacity of VSTM for single-feature objects (color) was investigated. Participants had to make a same-different comparison between two successively presented color patterns. Accuracy was found to be nearly 100% for patterns of one to three elements, but declined systematically as the pattern size increased from four to twelve elements. This led Luck and Vogel to estimate a capacity of VSTM for approximately four elements. In two further experiments, they provided evidence that this limitation does not originate from factors other than VSTM capacity (e.g., limitations associated with perceptual or decisional processes). Finally, they examined whether VSTM operates on separate featural or integrated object information of the elements. To do so, they introduced two conjunction conditions, one investigating VSTM capacity for conjunctions of two features (color x orientation) and one for conjunctions of four features (color x orientation x size x gap). Interestingly, performance in these two conjunction conditions did not differ from the single feature conditions. Luck and Vogel concluded that is not simply featural, but rather integrated object information that is coded in VSTM and that the VSTM limitation does not arise at the level of (object) features, but rather at that of objects: VSTM has “... a large capacity for retaining individual features as long as the features are confined to a small number of objects” (p. 280; but see Olson & Jiang, 2002, for conflicting results).

Yantis and Johnson (1990; Remington, Johnson & Yantis, 1992; Jonides & Yantis, 1988) investigated the visual processing of abrupt onset elements in a serial search task. When the target appeared at previously empty display location (i.e., when it was an *abrupt-onset element*), there was RT facilitation relative to when it was a *no-onset element* (i.e., when the target location was pre-occupied by a figure-eight placeholder that turned gradually, by deletion of component line segments, into the target). Importantly, the function relating search RTs to the number of abrupt-onset elements at first was characterized by a shallow increase up to four items, while that for no-onset elements exhibited a steep increase; thereafter, the two functions increased by equivalent rates. Yantis and Johnson attributed this pattern to a limited number of four ‘attentional priority tags’ being available, which are assigned to (up to four) abrupt onset elements on a competitive basis, giving them priority of focal-attentional processing over other (abrupt-onset and no-onset) elements.

A similar idea was proposed by Pylyshyn (e.g., Pylyshyn & Storm, 1988; Pylyshyn, 1989; Pylyshyn, Burkell, Fisher, Sears, Schmidt, & Trick, 1994; Burkell & Pylyshyn, 1997). According to his FINST (‘fingers of instantiation’) hypothesis, a number of up to five display items undergoing a salient (abrupt-onset) change can be automatically ‘indexed’ and processed as a subset of prioritized display items. Evidence for multiple indices was found in a multi-object tracking task (Pylyshyn & Storm, 1988) in which observers were able to simultaneously track and monitor four to five independently moving elements that were randomly selected (and made salient by an abrupt-onset manipulation) from a larger set of display elements.

Jiang and Wang (2004) reported facilitated processing for six to eight spatially disparate display locations/elements. When, one half of the display elements (including an element that was later revealed to be the target) was presented earlier (frame 1) than the other elements (frame 2) in a ‘*gap paradigm*’ (e.g., see Watson, Humphreys & Olivers, 2004), observers’ accuracy in detecting the target was nearly 100% when six new elements were presented, but was much poorer when twelve new elements appeared in frame 2. This led Jiang and Wang to estimate the positional capacity of VSTM as ranging from 5.6 (Experiment 2) to 7.8 spatial locations (Experiment 1).

Results reported by Müller and von Mühlenen (2000; see also Müller, von Mühlenen, & Geyer, submitted) may be taken to suggest that up to ten spatial elements/locations may be inhibitorily tagged in visual search. When observers had to discern the presence of a target in a visual search task followed by a speeded detection response to a probe-dot stimulus (see also Klein, 1988), Müller and von Mühlenen found a benefit in probe RT when the probe appeared at a formerly empty display location, as compared to the location of a search array stimulus (distractor). The RT benefit was larger in a search task that required serial shifts of focal attention, relative to a pop-out search task. This was interpreted as evidence for an 'inhibition of return' (IOR) mechanism (Posner & Cohen, 1984) operating in serial visual search. Of particular interest in the present context, the facts that (1) the search displays contained ten distractors (nine distractors on target-present trials) and (2) the distractors were randomly probed would suggest a VSTM capacity of ten locations/elements (see also Ogawa, Takeda, & Yagi, 2002, who found evidence of IOR when probing stimuli in dynamic displays with 8 moving elements).

Müller, von Mühlenen, and Geyer (submitted) found increased on-probe RT costs in a pop-out search task (10-element displays) relative to a passive-viewing task (in which observers simply viewed the display without carrying out a search). Müller et al. interpreted this finding in terms of another inhibitory mechanism similar to 'visual marking' (Watson, Humphreys, & Olivers, 2004), namely: the parallel inhibition of homogeneous distractors in visual (pop-out) search.

In summary, there appears to be a wide range of estimates for the spatial capacity of within-trial VSTM, which appear depend on the particular experimental paradigms used (from 4 up to 10 locations/elements, both for facilitatory and for inhibitory memory mechanisms). It is not clear, however, whether these estimates extend to the cross-trial priming effects demonstrated by Maljkovic and Nakayama, amongst others. The present experiments were designed to investigate this question, by systematically varying the number of distractors in the display (Experiment 1) and the spatial arrangement of the distractors (Experiment 2).

Overview of the present experiments

Experiment 1 was designed to examine the positional capacity of cross-trial VSTM. If trial-to-trial priming for positions was limited in positional capacity, the RT disadvantage (inhibition) for the presentation of a singleton target (trial *N*) at display positions occupied on previous trials (*N-1* etc.) by a distractor was expected to be dependent on display size. The results of Experiment 1 revealed a clear capacity limit for inhibitory priming: inhibition was found only when displays contained 2 distractors (i.e., when displays contained three elements: 1 target plus 2 distractors). In contrast, facilitation (for a target presented at a previous target location) was unaffected by the number of distractors. Furthermore, Experiment 1 revealed a strong effect of practice on the facilitatory and inhibitory effects for displays with a target and two distractors (the effects extended further back in time with increasing practice), which suggested that observers were exploiting the regularity of the stimulus arrangement to optimize task performance (the target and the two distractors were always presented in a simple, near-equilateral triangle configuration). To examine this possibility, in Experiment 2, the arrangement of the display elements (the separations of the distractor from the target and amongst themselves) changed unpredictably across trials, so that it was no longer possible to consistently apply a regular (near-equilateral triangular) frame to place facilitatory and inhibitory tags at the target and distractor locations. Interestingly, under these conditions, reliable evidence of facilitatory priming emerged only after extended practice, while there was no evidence at all of inhibitory priming (even after extended practice).

Overall, the pattern of results obtained in Experiment 1 and 2 suggests that positional cross-trial priming is limited in capacity to three display elements/locations. The dissociations between the facilitatory and inhibitory effects support the proposal that the priming of target (facilitatory) and, respectively, distractor locations (inhibitory) is based on different types of positional cross-trial memory. However, with regularly arranged displays, the two types of memory are likely to be linked by observers using a ‘top-down’ spatial reference frame (anchored on the target location) to assign inhibitory tags to distractor locations. This strategy fails (or is no longer operable) when the display arrangement varies randomly across trials.

Experiment 1

Experiment 1 was designed to examine the positional capacity of trial-to-trial priming. The search displays (see Figure 1) consisted of one unique-color target plus either two, three, five, or seven distractors. The target was either red and the distractors green, or vice versa. All stimuli were ‘diamond’-shaped, with a corner section missing to either the left or the right. Observers had to detect the unique color target and respond left (-hand) or right (-hand) according to the side of the missing corner section (‘compound task’). On a given trial *N*, the target could appear either at a previously (e.g., on trial *N-1*) empty location (‘neutral’ baseline), at a location occupied by a target, or at a location occupied by a distractor. Based on prior studies (in particular, Maljkovic & Nakayama, 1996), relative to the neutral baseline, facilitation of target detection and, consequently, RT was expected for targets appearing at the location of a previous target, and inhibition for targets appearing at the location of a previous distractor. Such a pattern would replicate the results reported by Maljkovic and Nakayama.

Furthermore, the systematic variation of the display size (i.e., the number of distractors) was intended to provide novel insights into the capacity of inhibitory priming, that is: How many previous distractor locations can be inhibited? This phrasing of the question assumes that a location is either tagged by inhibition or not, and there is a limited (integer) number of inhibitory tags available to be assigned to the various distractor locations. An alternative is: Does the inhibition depend on the number of distractor locations? This question allows for the possibility that, rather than being an all-or-nothing process, inhibition is based on a limited-capacity inhibitory resource, with resources allocated to locations in a graded fashion. Thus, if the number of locations exceeds the inhibitory capacity, all locations may be inhibited to a degree proportional to the total resource. The predictions are the same for the two underlying notions: If inhibitory priming is capacity-limited, then the RT disadvantage for a target presented at the location of a previous distractor should decrease as a function of display size. For the sake of simplicity, the predictions will be phrased in terms of the 'limited-number-of-inhibitory-tags' notion.

Assume, for instance, that inhibitory priming is limited to two (distractor) locations. Consequently, the RT disadvantage would be expected to be smaller when there are more than two ($i > 2$) rather than exactly two ($i = 2$) distractors in the display. If there are more than two (say 7) distractors at different locations, two of these will be tagged on a 'competitive' basis; these locations will be inhibited, while the status of the remaining (7-2=5) distractor locations would correspond to that of a previously unoccupied, 'neutral' location (i.e., they will not be inhibited at all). Since the target is equally likely to appear at all distractor locations, the resulting RT represents a mixture of instances when the target is presented at an actually inhibited location (in the example, 2 out of 7 locations) and when it is presented at a non-inhibited location (5 out of 7 locations). Thus, the larger the number of distractors locations, the less the influence of inhibition in determining the RTs for targets appearing at a previous distractor location, and the less the overall RT disadvantage for such locations.

That is to say: If the number of inhibitory tags available is seven (the maximum number of distractor locations in Experiment 1), the function relating RT to the number of distractor locations will be flat (i.e., relative to the neutral baseline, the RT disadvantage will be constant across display size). However, if the number of inhibitory tags is less than seven, then, after a flat section, the function converges towards an asymptotic level above the (neutral) baseline performance. The length of the flat section is determined by the number of distractor locations that can be inhibitorily tagged (the section is the longer, the greater the number of tags) – as is the asymptotic performance level and the rate of convergence (the less the number of tags, the closer to the baseline the asymptotic level and the greater the initial rate of convergence).

Method

Participants. Ten observers (age range from 20 to 27 years; four female; all reporting normal or corrected-to-normal vision) took part in Experiment 1. They were paid at a rate of € 8.00 per session.

Apparatus. The experiment was conducted in a dimly lighted laboratory, to minimize reflections on the monitor. Stimulus presentation and RT measurement were controlled by a standard PC (a 75 MHz Pentium I). Stimuli were presented on a 17-inch color monitor (at a frame rate of 60 Hz), with a resolution of 640 x 480 pixels. Observers viewed the monitor from the distance of approximately 60 cm, maintained by the use of a chin rest. They responded by pressing the right and, respectively, left buttons of a serial Microsoft mouse, with track ball removed to improve timing accuracy (Segalowitz & Graves, 1990).

Stimuli. The stimuli were red and green diamonds, all with a cut-off section to the left or right (with side determined randomly for each stimulus). There were always one target plus either two, three, five, or seven distractors in the display. The target was unique in color; when the target was red, the distractors were green, and vice versa (i.e., the target and distractor color changed randomly across trials). The colors were near-equiluminant: red, 7.7 cd/m^2; green, 8.0 cd/m^2. The screen background was black (luminance of 0.5 cd/m^2). The size of the diamonds was 1.2° x 1.2° of visual angle, with a cut-off section of 0.3° either to the left or the right side. The search elements were arranged on a near-circular ‘ellipse’, with horizontal and vertical axes of 17.5° and 14.0°, respectively. [Note that an elliptical ‘frame’ had also been used by Maljkovic and Nakayama (1996). The reason for this was to compensate for the normally faster responses to targets on the horizontal compared to the vertical meridian of the display (e.g., Kröse & Julesz, 1989).] The center of the ellipse was marked by a white fixation point, 0.5° x 0.5° in size and 13.7 cd/m² in luminance.

The singleton color target could appear at any one of 24 possible locations around the circumference of the ellipse. The distractors were then positioned such that the distances between adjacent stimuli on the circumference (target-distractor and distractor-distractor distances) were equal (e.g., with a target and two distractors, the separation between adjacent locations was 24/3 = 8 [with 7 intervening] locations; with a target and five distractors, the separation was 24/6 = 4 [with 3 intervening] locations; etc.). See Figure 1 for illustrations of the four distractor conditions of Experiment 1.

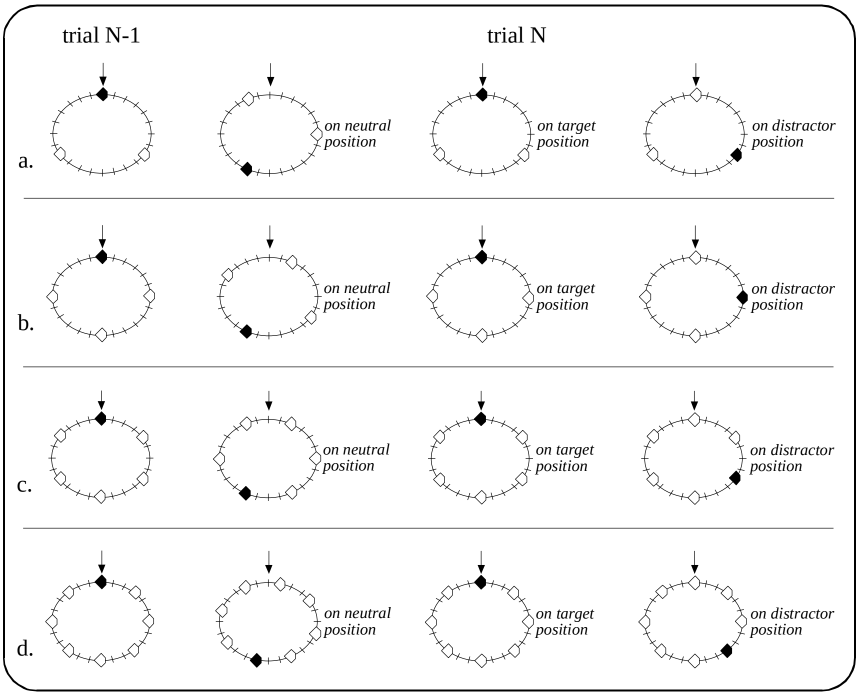

Figure 1. Examples of the four distractor conditions in Experiment 1 (see panels *a*, *b*, *c*, and *d*), with singleton color target appearing among 2, 3, 5, and 7 distractors, respectively. For each condition, it is illustrated where the target on a given trial *N* could appear with respect to the previous trial *N-1*. The distractor condition was constant throughout a trial block, while the location, color, and 'orientation' (i.e., side of cut-off segment) of the target (and distractors) varied randomly from trial to trial. Observers had to respond to the orientation of the singleton color target. (The near-circular ellipses, around which the target and distractors were arranged, were not shown in the experimental displays; they are added here only for purposes of illustration.)

Design and procedure. With respect to the position of the target on the previous trial *N-1*, the target on the current trial *N* could appear at either of three types of location: a neutral (neither target nor distractor, i.e., an empty) location (*target on neutral location*), a target location (*target on target location*), or a distractor location (*target on distractor location*). The orientation (i.e., the side of the cut-off sections) of the targets on the previous and current trials could either be *same* (both left or both right) or *different* (the first left and the second right, or vice versa).

The experiment consisted of 3,000 experimental trials, with 375 trials for each Distractor (2, 3, 5, 7) x Target orientation (same, different) combination. Since there were 24 possible target and distractor locations on the ellipse (with at most eight stimuli), it was highly probable that a target on trial *N* was presented at a location that was neutral on trial *N-1* (and less probable that it was presented at the location of a distractor or a target on trial *N-1*). Thus, to provide at least 16 observations for target-at-target-location and at least 32 observations for target-at-distractor-location conditions [1], the total number of trials was set to 3,000.

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[1] In Experiment 1, there were 3,000/4 = 750 trials for each number-of-distractor conditions (2, 3, 5, or 7) and 750/2 = 375 trials for each target orientation (same, different). Because there were 24 possible target (and distractor) locations, the target could appear with a probability of 1/24 on a previous target and 1/12 on a previous distractor location (2-distractor condition), leading to at least 16 (375 x 1/24) observations in the target-on-target location and 32 (375 x 1/12) observations in the target-on-distractor location conditions. In the other conditions (with 3 or more distractors), the probabilities (and consequently the number of observations) that the target was presented on a previous distractor location were much higher.

The location, color, and orientation of the target was varied randomly from trial to trial. The color and location of the target determined the color and locations of the distractors. When the target was red, the distractors were green, and vice versa. When the target appeared, say, at the top of the ellipse in the 2-distractor condition, the distractors were positioned at a distance of 8 location units in the bottom left and right sections of the ellipse, with the target and distractors forming a regular (near-equilateral), upward-pointing triangle; in the 3-distractor condition, the distances between adjacent stimuli were 6 location units, with the stimuli forming a regular (near-) square or, respectively, diamond arrangement; and analogously for the 5- and 7-distractor conditions. The number of distractors was held constant within each trial block, but it was varied randomly across blocks.

At the beginning of each trial, a fixation cross was presented in the center of the monitor. After 1,000 ms, the search array was displayed (with the fixation cross remaining on) until the observer responded to the orientation (i.e., the side of the cut-off section) of the target by pressing the left or the right mouse button, respectively, using the index finger of the corresponding hand. The response was followed by a blank screen for 1,000 ms, after which the next display was presented. Error feedback (an error occurred when the right section of the target was cut off and the observer pressed the left button, and vice versa) was not provided.

The experiment consisted of three sessions (each of about 50 minutes), which were conducted on three separate days. Each session consisted of eight blocks with five (unrecorded) warming-up trials and 120 experimental trials, with blocks separated by short breaks. At the beginning of the first session, observers performed one block of 100 practice trials (data not recorded).

Results

For each experimental condition (distractor condition x target orientation x target location), RTs outside the range of ?2.5 standard deviations (SD) from the mean were discarded as ‘outliers’ (overall, 2.4% of trials). Error-response trials were also excluded from the analysis (3.7% of all trials; for further details, see ‘accuracy’ results below). When examining for the effects of repetition, the current trial may have been influenced by the preceding trial or it may have influenced the subsequent trial. Therefore, responses on trials that preceded or followed an erroneous response were not analyzed. In other words, repetition effects were analyzed only for two consecutive trials on which the responses were correct.

The results are presented in the following sections, first for the first-order positional repetition effects on RT and response accuracy, followed by the higher-order repetition effects.

DISTRACTOR CONDITION	***2***		***3***		***5***		***7***	
TARGET POSITION	RT	DIFF	RT	DIFF	RT	DIFF	RT	DIFF
AT NEUTRAL POSITION	733		703		672		687	
AT TARGET POSITION	694	-39	676	-27	649	-23	640	-47
AT DISTRACTOR POSITION	761	28	710	7	679	7	698	11

Table 1: Mean correct RTs (in ms) in Experiment 1 to the singleton color target on trial *N* dependent on the number of distractors (2, 3, 5, 7) and the target position (at neutral location, at target location, at distractor location on trial *N-1*); the RTs are averaged across the target orientation conditions (same/different orientation of target N relative to target N-1). Also given is the size of the RT difference (*DIFF*) for target-at-target and target-at-distractor location conditions relative to target-at-neutral location condition (i.e., RT facilitation and inhibition, respectively).

First-order repetition effects. First, the RTs to the target on trial *N* were examined dependent on the location of target *N* in relation to the target and distractor locations on trial *N-1* (‘first-order repetition’ effects). To this end, a repeated-measures analysis of variance (ANOVA) was carried out with the factors: distractor number (2, 3, 5, 7), target orientation (same, different), and, importantly, target position (at a location that was neutral, a target location, or a distractor location on trial *N-1*). This ANOVA revealed the main effects of distractor number [$F(3,27) = 9.73$, $p < .01$, $MS_E = 4,764$] and target position [$F(2,18) = 30.05$, $p < .01$, $MS_E = 1,582$] as well as the interaction between distractor number and target position [$F(6,54) = 4.96$, $p < .01$, $MS_E = 368$] to be significant. Post-hoc (Tukey LSD) tests were carried out to further analyze these effects.

The effect of number of distractors occurred because detection of the singleton target was significantly expedited when it was presented amongst three, five, or seven distractors (696, 667, and 674 ms, respectively) rather than just two distractors (729 ms). This is consistent with previous work that has revealed target ‘pop-out’ to be more efficient when targets and distractors are closely, rather than widely, placed relative to each other (probably because feature-contrast computation is spatially scaled; e.g., Bravo & Nakayama, 1992; Nothdurft, 1991; Krummenacher, Müller, & Heller, 2002a).

The main effect of target position was due to the fact that RTs were fastest when the target on trial *N* appeared at the same location as the target on trial *N-1* (665 ms), intermediate when it was presented at a neutral position (699 ms), and slowest when it appeared at the location of a distractor (712 ms). Thus, relative to the neutral baseline, there was facilitation of 34 ms, overall, for targets at previous target locations, and inhibition of 13 ms for targets at previous distractor locations.

Importantly, the distractor number x target location was also significant. This interaction (see Table 1) reflects the fact that, while the facilitatory effect was reliable for all number-of-distractor conditions (despite exhibiting some non-systematic variability), the inhibitory effect showed an (asymptotic) decrease with increasing number of distractors: with 3 or more distractors, the inhibition was no longer reliable. This pattern of effects suggests that there is a limit to the distractor locations that can be inhibitorily tagged, and the limit is two locations at most.

However, it may be that inhibition is reduced for displays with larger numbers of distractors because the target on trial *N* might appear at a distractor location that was relatively close to the target location on trial *N-1* (the more distractors, the closer some of them to the target). Assuming that there is a gradient of facilitation around the target location, distractor locations close to the target might receive some facilitation (counteracting any inhibition). Now, when there are more distractors in the display, the nearer some of them are to the target. As a result, by averaging inhibitory effects across near and far distractor locations, the (real) magnitude of inhibition (outside the area of facilitation) would be underestimated. To examine this possibility, RTs to targets on trial *N* presented at the location of a distractor on trial *N-1* were analyzed as a function of the distance, measured in degrees of visual angle, between the distractor and target locations on trial *N-1* (data from the 3-, 5-, and 7-distractor conditions). The data are presented in Figure 2, which shows no systematic variation in target-on-distractor-location RTs as a function of the distance of the distractor from the target on trial N-1 (the baseline in Figure 2 is the average RT for targets at neutral locations across the 3-, 5-, and 7-distractor conditions). To examine whether the inhibitory effect (distractor location RT minus neutral location RT) varied as a function of distance from the target location, a repeated-measures ANOVA was carried out with the factors distance (5.9, 7.7, 11.0, 13.6, 14.4, 15.6°) and target position (target at neutral location, at distractor location). Of most interest to this question, the ANOVA revealed only a marginally significant interaction [$F(5,45)=1.98$, $.10>p>.05$, $MS_E=80$], with inhibition showing no systematic variation with distance.

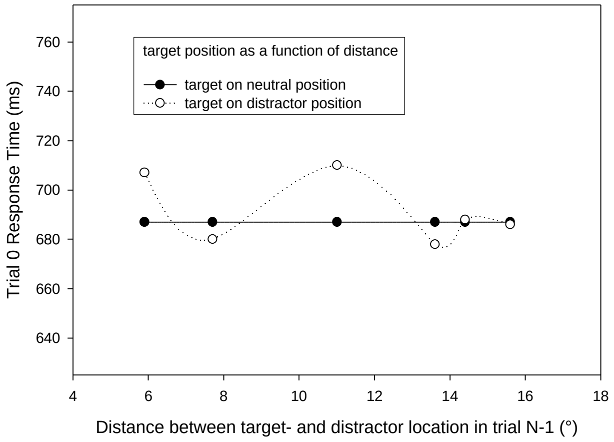

Figure 2. Experiment 1: Mean correct RTs to targets on trial *N* presented at the location of a distractor on trial *N-1*, as a function of the distance [in degrees of visual angle] between the distractor and target locations on trial *N-1*. Open circles represent the RT on trial *N* for a given distance between the target and distractor locations on trial *N-1*; filled circles represent the average RT (N) across all distances between target and neutral locations on trial *N-1* [baseline] (combined across the 3-, 5-, and 7-distractor conditions).

Observers' individual error rates (which ranged between 0.7% and 7.1% overall) were analyzed by an ANOVA analogous to that used to examine the RTs. This ANOVA failed to reveal any significant main effects. The only effect that reached significance was the target location x target orientation interaction. When the target appeared at a neutral location, the repetition/non-repetition of the orientation of the target had little effect on accuracy (average error rates of 4.0 % vs. 3.7 % for same vs. different orientations). This was also the case when the target was displayed at the location of a distractor location on the previous trial (4.0% vs. 4.2%). However, when the target was presented at the location of the target on the previous trial, accuracy was significantly better when target orientation was repeated rather than changed (1.2% vs. 5.1%). This suggests a link between observers' implicit target location and orientation 'expectancies' (e.g., Kingstone, 1992): if the location is repeated, there is a bias towards expecting the orientation to be repeated as well, even though this expectancy is wholly unfounded in terms of event statistics (see Müller & Krummenacher, 2005, and

Pollmann, Weidner, Müller, & von Cramon, 2005, for a discussion of such ‘linked-expectancies’ effects in visual search tasks). Overall, however, response accuracy was relatively balanced across the target location (3.2%, 4.1%, and 3.9% for target at target, distractor, and neutral locations, respectively) and number-of-distractors conditions, arguing against the RT effects being confounded by speed-accuracy trade-offs.

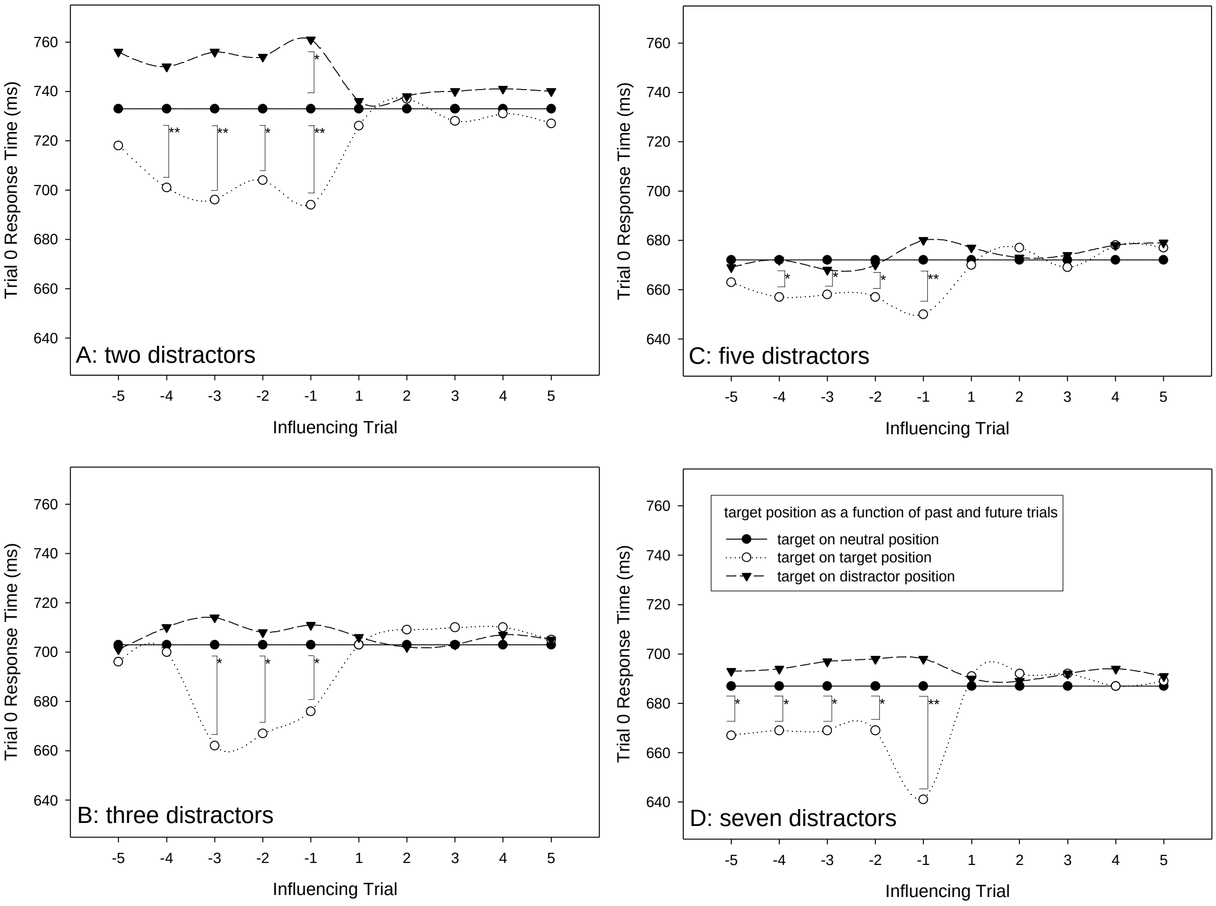

Figure 3: Experiment 1: Mean correct RTs to targets on trial *N* presented at neutral (filled circles), target (open circles), and, respectively, distractor locations (triangles) on previous trials *N-j* or subsequent trials *N+j*, separately for the four distractor conditions. Re-presentation of target *N* at a previous target location produced RT facilitation (relative to the neutral baseline), for influencing trials *N-1* through *N-5*. Presentation of target *N* at a previous distractor location produced RT inhibition, but only in the 2-distractor condition and for influencing trial *N-1*. [RTs were unaffected by whether target N appeared at a future (*N+j*) neutral, target, or distractor location.]

Higher-order repetition effects. The higher-order repetition effects on response time are shown in Figure 3, which presents the mean RTs to the target on trial *N* dependent on the location of target *N* with reference to the target and distractor locations on the preceding trials *N-j* and the subsequent trials *N+j*, separately for the four distractor conditions (see the various panels of Figure 3). For example, the three data points presented for trial *N-2* present the RT on trial *N* when target *N* appeared at either a neutral, the target, or a distractor location on trial *N-2*. However, since the target on trial *N-1* (more generally, on any intervening trial between *N* and *N-j*) may have appeared on a non-neutral location (e.g., the location of the target or a distractor on trial *N-2*), the RT to the target on trial *N* (as a function of trial *N-2*) could have been affected by the location of the target on trial *N-1* (e.g., the target on trial *N* appeared at the position of a distractor on trial *N-2*, but at the position of the target on trial *N-1*). To rule out such effects, all trials on which the target was presented at a non-neutral location on any intervening trial were excluded from analysis (very few trials overall).

To examine facilitatory and inhibitory effects caused by preceding (*N-j*) and subsequent trials (*N+j*) [the latter were examined only for control purposes: later trials in the sequence could not have logically influenced the response on an earlier trial and may, therefore, be taken to provide a random-effect baseline], Tukey LSD post-hoc tests were conducted for each of the four distractor conditions (based on separate ANOVAs, with the factors target position and influencing trial), comparing RTs to targets at target locations (facilitation) and to targets at distractor locations (inhibition) relative to targets at neutral locations.

Figure 3 shows that, while RT facilitation for targets at target (relative to neutral) locations was larger overall and maintained across longer sequences of (3 to 5) trials, inhibition for targets at distractor locations was smaller overall (if at all present) and dissipated over shorter sequences of trials (in the 2-distractor condition, it was no longer significant after 1 trial).

In more detail, the RT facilitation for targets at target locations was significant for preceding trials *N-1* through *N-3* in the 3-distractor condition, *N-1* through *N-4* in the 2- and 5-distractor conditions, and *N-1* through *N-5* in the 7-distractor condition. The only significant RT inhibition for a target presented at a distractor location was observed in the 2-distractor condition for trial *N-1*, but not trials *N-2* through *N-5*, though a tendency towards inhibition was evident for all these trials. In summary, facilitation was relatively robust and long-lasting, while inhibition was observed only with 2-distractor displays and tended to be shorter-lasting. [In all four distractor conditions, later trials (*N+j*) did not affect observers' performance on trial *N*, as expected.]

Comparison of the facilitatory effects among the four distractor conditions. Figure 3 suggests the amount of facilitation for a previous target position to be dependent on the distractor condition: facilitation appeared somewhat smaller in the 3-, 5-, and 7- relative to the 2-distractor condition. [Because the overall RTs were faster in the 3-, 5-, and 7- relative to the 2-distractor condition, the tendency for facilitation to be reduced in the former conditions possibly reflects a ceiling effect, that is: the facilitatory effect could not be improved because of the efficient 'pop-out' of the target among more closely spaced display elements.] To examine whether the amount of facilitation was reduced in the 3-, 5-, and 7- relative to the 2-distractor condition, a separate repeated-measures ANOVA of the facilitatory effect (estimated by the difference target-at-neutral location RT minus target-at-target location RT), with the factors distractor condition and influencing trial, was carried out. While the main effect of distractor condition turned out to be non-significant [$F(3,27)=1.10$, $p>.30$, $MS_E=1,840$], the two-way interaction was marginally significant [$F(12,108)=1.69$, $.10>p>.05$, $MS_E=560$]. Thus, while the amount of facilitation was independent of the distractor condition, facilitation tended to reach back further in the 2- as compared to the remaining distractor conditions. Note that the main effect of influencing trial was also significant [$F(4,36)=3.57$, $p<.02$, $MS_E=776$]. Tukey LSD post-hoc tests revealed the facilitatory effect to be largest for trial *N-1* (34 ms), intermediate for *N-2* and *N-3* (25 and 28 ms), and smallest for trials *N-4* and *N-5* (17 and 13 ms).

Comparison of the inhibitory effects among the four distractor conditions. Although the separate ANOVAs for the individual distractor conditions had failed to reveal inhibition to be reliable when displays contained more than two distractors, this (non-) finding may simply reflect the fact that, with larger numbers of distractors, net inhibitory effects become smaller due to some (if not the majority of) distractors/distractor locations not receiving any inhibition at all (or, alternatively, by all distractors/distractor locations receiving a reduced amount of inhibition). If this were the case, inhibitory tendencies evident in these conditions (with 3, 5, and 7 distractors) could contribute towards a more precise mapping of the time course/temporal extension of inhibitory effects, by averaging inhibition across all distractor conditions (which would cancel out random effects affecting the data in the individual distractor conditions). [While permitting a more precise mapping of the time course, the magnitude of the inhibitory effect would, of course, be underestimated by this averaging process.] To examine the time course of inhibition across distractor conditions, a separate repeated-measures ANOVA of the inhibitory effect (i.e., target-at-distractor location RT minus target-at-neutral location RT), with the factors distractor condition and influencing trial, was carried out. This ANOVA revealed the effect of distractor condition to be significant [$F(3,27)=10.19$, $p<.01$, $MS_E=440$], reflecting the fact that inhibition was larger in the 2- relative to the other distractor conditions. More importantly, there were no significant effects of influencing trial [main effect: $F(4,36)=.61$, $p>.60$, $MS_E=539$; influencing trial x distractor condition interaction: $F(12,108)=.40$, $p>.90$, $MS_E=286$], suggesting the magnitude of inhibition to be relatively constant across trials *N-1* through *N-5* (in contrast to facilitation; see above).

Discussion

Experiment 1 was designed to examine the capacity of priming for spatial locations in a pop-out search task, in which the number of distractors in the search display was systematically manipulated. Repetition of the target location was found to influence performance across sequences of trials: RTs were overall fastest when the current target appeared at the location of a previous target, independently of the number of display elements. In contrast, when the target appeared at the location of a previous distractor, RTs tended to be slowest, but significantly so only in the 2-distractor condition.

The pattern of inhibition is important because it suggests that the capacity of inhibitory priming is limited to two (distractor) locations. This limitation appears at variance with previous reports of a larger capacity of VSTM in a variety of (within-trial) visual tasks (e.g., Phillips, 1974; Yantis & Johnson, 1990; Müller & von Mühlenen, 2000), and may be taken to provide evidence for the distinction between within-trial memory and trial-to-trial priming (in terms of not only their temporal, but also their spatial attributes; for the latter, see Experiment 2 below).

The fact that RT facilitation, in contrast to inhibition, was uninfluenced by the number of display elements suggests that that memory mechanism underlying facilitatory priming is relatively separate from that supporting inhibitory priming (i.e., priming consists of two distinct memory components, one for target location [or, more generally, target features] and one for distractor location [or features]).

Furthermore, the fact that locational priming was only slightly affected by repetition of target orientation, the memory seems to be operating on search-relevant (perceptual), rather than response-based information, consistent with previous findings (e.g., Maljkovic & Nakayama, 1994, 1996, 2000; Hillstrom, 2000; Krummenacher at al., 2002). But see Cohen and Magen (1999; Cohen & Shoup, 1997, 2000) who advocated the opposite position. They proposed that the various feature dimensions (color, orientation, etc.) possess separate response selection mechanisms and that it is not the feature coding mechanisms, but rather the response selection mechanism that is primed by target repetition. However, this proposal cannot account for the present findings, which revealed the repetition/non-repetition of the target's orientation to have at best a marginal effect on positional priming.

The inhibitory effect in Experiment 1 did not show (robust) persistence beyond trial *N-1*. In contrast, in Maljkovic and Nakayama's (1996) experiments, the effect of presenting a target at the location of a distractor was evident for the last five to eight trials. It is not clear why this difference was obtained, but at least two critical points may have contributed to the discrepant results of Experiment 1: (i) the present observers (though more in number) were less practiced than those participating in Maljkovic and Nakayama's experiments (mainly the authors themselves); and (ii), in the present experiment, the target (and the distractors) could appear at 24 display locations, which compares with only 6 (or 12) locations as in Maljkovic and Nakayama's experiments. With respect to point (ii), the probability for a target to appear at any of the two distractor locations was at least twice as high in the case of 6 (33.3 %) or 12 (16.6 %) as in the case of 24 locations (8.3 %). In contrast, the probability for a target to appear at a neutral location was much higher in the case of 24 (87.5 %) than in the case of 6 (50.0 %) or 12 (75.0 %) locations. It is conceivable that these reversed 'statistics' diminished the inhibitory effect in Experiment 1, because on a 'subsequent' trial it was highly likely that the target (re-)appeared at a previously neutral, rather than a distractor, location. Such a 'positional uncertainty' could not only have affected the temporal, but also the spatial component of inhibitory priming, which would leave the possibility that the positional capacity of the underlying memory is much higher. However, the fact that a target location was associated with facilitation up to trial *N-5* would argue against such an account and instead suggests that positional uncertainty had no (or only a small) effect on the spatial characteristics of priming.

In the present experiment, observers were less practiced than in Maljkovic and Nakayama's studies. In their experiments, the authors themselves served as observers, performing between 3,400 and 5,600 trials. The less extended practice of the present observers might also have contributed to the finding that inhibition of distractor locations was significant only for trial *N-1*.

To examine for practice effects in Experiment 1, the RTs on trials 1 through 1,000 ('unpracticed' performance) and trials 2,001 through 3,000 ('practiced' performance) were re-analyzed separately for each distractor condition by repeated-measures ANOVAs with the factors practice (practiced, unpracticed), target location (target on neutral location, target on target location, target on distractor location), and influencing trial (*N-i*).

The results are presented in Figure 4. As can be seen, in the 3-, 5-, and 7-distractor conditions, practice led to overall faster RTs (main effects of practice: F(1,9)=8.18, p<.02, MS_E=79,115; F(1,9)=8.68, p<.02, MS_E=79,955; and F(1,9)=6.11, p<.05, MS_E=67,275 in the 3-, 5-, and 7-distractor conditions, respectively). But facilitation was not reliable increased in the last, as compared to the first, 1,000 trials (the interactions practice x target location in the ANOVAs of the 3-, 5-, and 7-distractor conditions were non-significant), although there appeared to be some (non-significant) tendency for facilitation to extend back across a larger number of trials intervening between the current trial *N* and the influencing trial *N-5* [three way interactions: F(8,72)=1.31; p>.25; MS_E=941; F(8,72)=.25; p>.90; MS_E=382; and F(8,72)=1.70; p>.10; MS_E=445 in the 3-, 5-, and 7-distractor conditions, respectively]. Similarly, the inhibitory effects exhibited only non-significant improvement with practice in the 3-, 5-, and 7-distractor conditions.

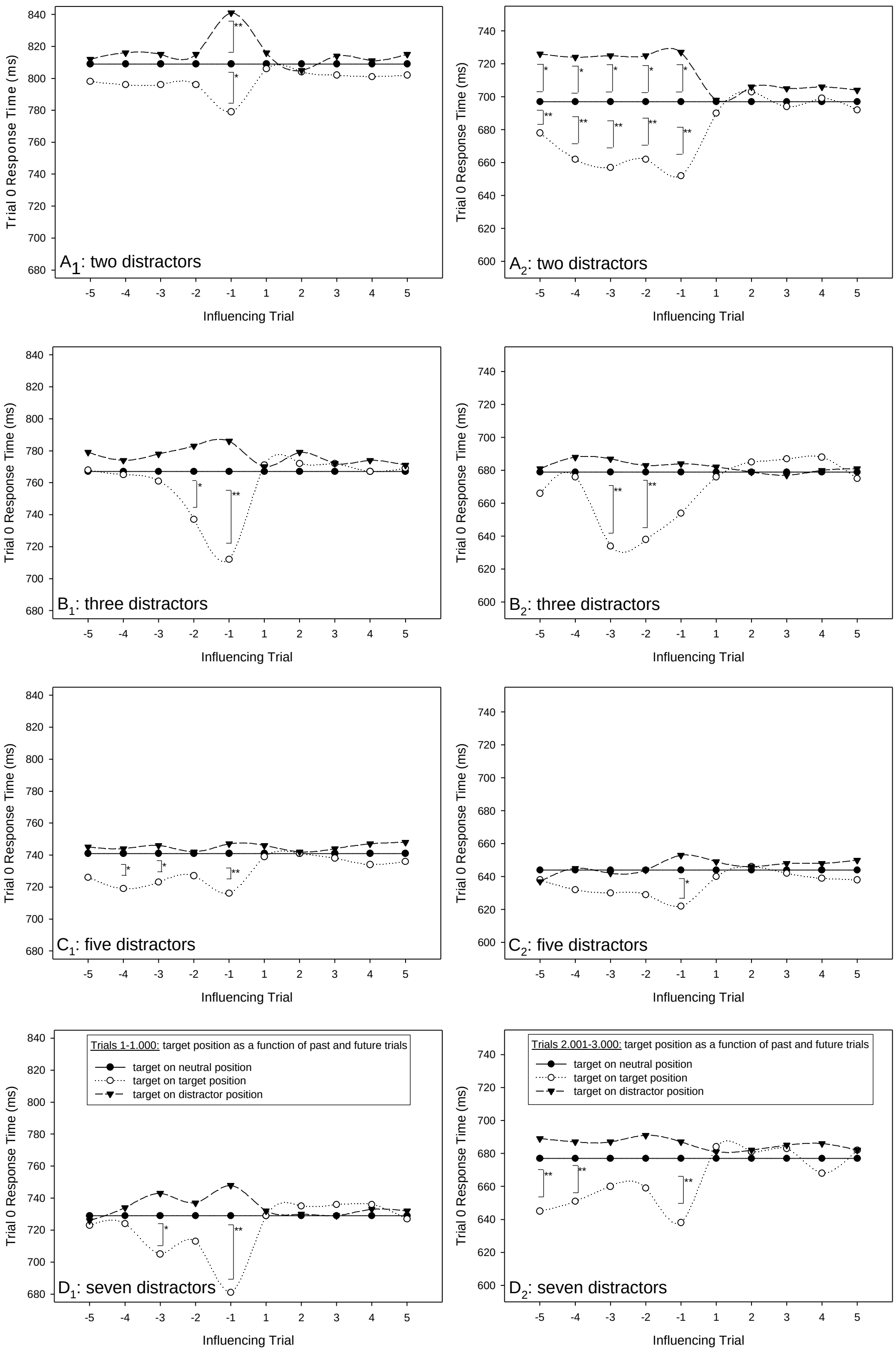

Figure 4. Experiment 1: Mean correct RTs to targets on trial *N* presented at neutral (filled circles), target (open circles), and, respectively, distractor locations (triangles) on previous trials *N-j* or subsequent trials *N+j*, separately for the four distractor conditions (panels from top to bottom) and dependent on the amount of practice on the task (left-hand panels: trials 1–1,000; right-hand panels: trials 2,001–3,000). While practice expedited RTs in all distractor conditions, it enhanced RT facilitation and inhibition only in the 2-distractor condition, not (or only little) in the 3-, 5-, and 7-distractor conditions.

However, in contrast to the 3-, 5-, and 7-distractor conditions, practice did have a stronger effect on performance when displays contained only two distractors. On the one hand, as indicated by the significant interaction practice x target location [$F(2,18)=4.34$, $p<.05$, $MS_E=1,903$], there was a robust increase in the strength of facilitation (an ANOVA comparing the target-at-target- against the target-at-neutral-location condition only revealed the overall facilitation to be larger in the last, relative to the first, 1,000 trials; interaction practice x target position: $F(1,9)=10.57$, $p<.01$, $MS_E=3,014$). On the other hand, there was also a robust increase in inhibition (an ANOVA comparing the target-at-distractor- against the target-at-neutral-location condition only revealed the overall inhibition to be larger in the last, relative to the first, 1,000 trials; interaction practice x target position: $F(1,9)=5.54$, $p<.05$, $MS_E=659$). Note that, despite the trends apparent in Figure 5, the interaction practice x target position x influencing trial in the facilitation and inhibition ANOVAs were non-significant (suggesting that facilitation and inhibition did not extend significantly further back in time in the last relative to the first 1,000 trials).

In other words, practice led to enhanced and temporally extended facilitatory and inhibitory priming – a pattern that is akin to that reported by Maljkovic and Nakayama (1996)[2].

This raises the question as to the cause of the more robust (and temporally extended) priming effects that are developed over the course of practice with three stimuli (1 target and 2 distractors), as compared to four and more stimuli, in display. One possibility is that practice improved observers' ability to utilize the regular stimulus arrangement (and its 'rotation' across trials) to guide their search. In the 2-distractor condition, the three display stimuli were always arranged as a regular (near-equilateral) triangle, which, phenomenally, appeared to rotate around the ellipse from trial to trial (with one reference point 'marked' within the triangular arrangement: the target location). Observers could have used this apparent triangle (arrangement) to pinpoint the target (in terms of an 'anchor point) and, as an automatic consequence, facilitate the target and inhibit the distractor locations more efficiently. In contrast, when there were four or more stimuli (3 or more distractors) in the display, the stimulus arrangement was less ‘informative’ (square/diamond, hexagon, octagon; this made it harder, in particular, to reference distractor locations). Accordingly, observers were less able (if at all) to benefit from the regular arrangement in improving their search performance, using facilitatory and, in particular, inhibitory priming of target and distractor locations, respectively. [It is also possible that, with larger numbers of distractors in the display, observers had no need to use such a cross-trial memory-based strategy because target ‘pop-out’ approached asymptotic efficiency, due to the closer spacing of the distractors on a given trial.] Experiment 2 was designed to test this idea, namely, that (with small numbers of distractors) simplicity/regularity of display arrangement is crucial for the efficient use of positional priming.

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[2] There was evidence of a dissociation between facilitatory and inhibitory priming effects as far as there was some practice-dependent enhancement of facilitation even when displays contained more than two distractors, while enhancement of inhibition was manifest only with two distractors in the display. Despite this, the possibility remains that the two types of enhancement are linked, that is: enhanced facilitation may be associated with enhanced inhibition, possibly because they derive from the same underlying learning effect exploiting the regular triangular arrangement of the target and the two distractors (i.e., learning to allocate one facilitatory and two inhibitory tags to equidistant locations within in a triangular display configuration; for evidence, see Experiment 2 below). This ‘strategy’ is probably acquired implicitly, and it may work only with triangular (and to some extent square) element arrangements, but not with complex configurations. ‘Implicit’ learning means that observers are unable to consciously reconstruct the target and distractor location on trial *N*-5.]

Experiment 2

In the 2-distractor condition of Experiment 1, the facilitatory and inhibitory effects deriving from the repetition of the target and distractor locations, respectively, were stronger and longer lasting in the last, relative to the first, experimental 1,000 trials. The dissociation in the enhancement of facilitation between the 2- and the other distractor conditions may have been due to observers having learned (perhaps implicitly) to use the regular triangular arrangement of the display elements to enhance their performance (by spatially referencing the target and distractor locations and allocating tags accordingly). Thus, factors other than simple (i.e., passive and non-strategic) facilitatory and inhibitory tagging of target and (all) distractor locations, respectively, may have played a critical role in producing the results of Experiment 1.

Experiment 2 was designed to examine this hypothesis, by eliminating a (positional-memory) strategy based on the simple, regular arrangement of the display elements in the 2-distractor (3-display element) condition. This was done by randomly varying the separations between the target and distractor locations (and thereby the regularity of their arrangement) across successive trials. If stimulus arrangement was critical for determining positional priming effects in Experiment 1, no effects of the previous target and distractor locations on the processing of the current target were expected. In contrast, if a simple (i.e., passive and non-strategic) memory was responsible for the results of Experiment 1, the inhibitory and facilitatory effects were expected to be unaffected by the random variation of target-distractor separations.

Method

The design and procedure in Experiment 2 were the same as in Experiment 1, with the following exceptions:

Participants. 10 unpracticed observers (five female; ages ranging from 21 to 27 years; all reported normal or corrected-to-normal vision) took part in Experiment 2. They performed the experiment within a single session that lasted about 40 minutes.

Design and procedure. On all trials, the singleton color target appeared amongst two distractors (2-distractor condition in Experiment 1). The independent variables were target orientation (same, different) and target position (target at neutral, at target, at distractor location). The total number of trials was 750, with 375 trials for each target orientation and at least 16 and 32 trials in the target-on-target- and the target-on-distractor-location conditions, respectively. [Note that the total number of trials was the same as in the 2-distractor condition of Experiment 1 (though, in Experiment 2, observers performed all 750 trials within a single session).]

As in Experiment 1, the color, orientation, and position of the singleton target changed randomly across trials. However, in contrast to Experiment 1, the distances between the display elements were variable, that is, the locations of two distractors were determined independently of that of the target, that is, without the distractors maintaining a fixed (simple, regular, predictable) spatial relation with reference to the target. The target was equally likely to appear at any of the 24 locations (p=1/24) on the ellipse, and there was a probability of 1/23 and 1/22 for the first and second distractor, respectively, to appear at any of the remaining positions within the ellipse. That is, there was a total of 24 x 23 x 22 (=12,144) potential target and distractors locations on a given trial. The experiment consisted of ten blocks, each of five (unrecorded) warming-up trials and 70 experimental trials, with blocks separated by short breaks. At the beginning of the experiment, observers performed one block of 50 practice trials (data not recorded).

Results

In Experiment 2, the same outlier filtering procedure was used as in Experiment 1, which led to the elimination of 2.6 % of all responses from further analysis.

EXPERIMENT	***2***		***1***	
TARGET POSITION	RT	DIFF	RT	DIFF
AT NEUTRAL POSITION	674		733	
AT TARGET POSITION	658	-16	694	-39
AT DISTRACTOR POSITION	676	2	761	28

Table 2: Mean correct RTs (in ms) to the singleton color target on trial *N*, dependent on the position of the target (at neutral location, at target location, at distractor location on trial *N-1*); the RTs are averaged across the target orientation conditions (same/different orientation of target N relative to target N-1). Also given is the size of the RT difference (*DIFF*) for target-at-target and target-at-distractor location conditions relative to target-at-neutral location condition (i.e., RT facilitation and inhibition, respectively). The left- and right-hand entries present the data of Experiment 2 and Experiment 1 (2-distractor condition), respectively.

First-order repetition effects. Table 2 presents the RTs to the target on trial *N* dependent on its location with reference to that of the target on trial *N-1*. Also listed are the RT differences, relative to the neutral baseline, for targets appearing at an *N-1* target (facilitation) and an *N-1* distractor location (inhibition), respectively – along with the facilitatory and inhibitory effects observed in the corresponding 2-distractor conditions of Experiment 1. The RTs in Experiment 2 were examined by means of a repeated-measures ANOVA with the factors target orientation (same, different) and target position (target at neutral location, at target location, at distractor location), which failed to reveal any effects to be significant. [An analogous ANOVA of observers’ error rates (which ranged between 1.7%

and 7.6%, with an average of 4.4%) also failed to reveal any significant effects.] As can be seen from Table 2, while there was some evidence of RT facilitation when target *N* was presented at the *N-1* target location (16 ms, which compares with 39 ms in Experiment 1), there was no evidence of any inhibition when the target on trial *N* was presented at an *N-1* distractor location (2 ms, which compares with 28 ms in Experiment 1).

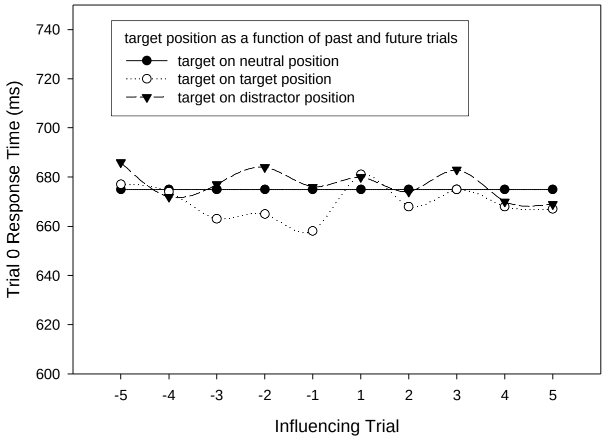

Figure 5. Experiment 2: Mean correct RTs to targets on trial *N* presented at neutral (filled circles), target (open circles), and, respectively, distractor locations (triangles) on previous trials *N-j* or subsequent trials *N+j*. Re-presentation of target *N* at a previous target location produced no RT facilitation (relative to the neutral baseline); and presentation of target *N* at a previous distractor location produced no inhibition. [RTs were unaffected by whether target N appeared at a future (*N+j*) neutral, target, or distractor location.]

Higher-order repetition effects. The higher-order repetition effects are shown in Figure 5, which presents the mean RTs to the target on trial *N* dependent on the location of target *N* with reference to the target and distractor locations on the preceding trials *N-j* and the subsequent trials *N+j*. As can be seen from Figure 5, and as confirmed by Tukey LSD post-hoc tests, there was neither any significant facilitation from preceding trials beyond N-1 (some numerical facilitation was present for trials *N-1* through *N-3*), nor was there any inhibition from any preceding trials in the range *N-1* through *N-5*.

Effects of practice on positional facilitation and inhibition. Figure 6 presents the mean correct RTs to the target on trial *N* dependent on whether it appeared at a neutral, a target, or a distractor location on the preceding trials *N-j* and subsequent trials *N+j*, separately for trials 1 through 250 and 501 through 750. To examine for practice effects in Experiment 2, the RTs on the first 250 (‘unpracticed’ performance) and last 250 trials (‘practiced’ performance) were re-analyzed in a repeated-measures ANOVA, with the factors practice (practiced, unpracticed), target location (target at neutral location, at target location, at distractor location), and influencing trial (*N-j*). This ANOVA revealed only the main effect of practice [F(1,9) = 8.95, p < .02, MS_E = 58,780] and the three-way interaction [F(8,72) = 2.39, p < .05, MS_E = 622] to be significant. The main effect of practice occurred because target detection performance was improved overall on the last relative to the first 250 trials (636 and 719 ms, respectively). The three-way interaction was due to the fact that RTs were significantly expedited when the target on trial N appeared at a trial *N-1* target location, relative to a neutral location, within the last 250 trials (607 and 637 ms for the target on target and target on neutral locations, respectively).

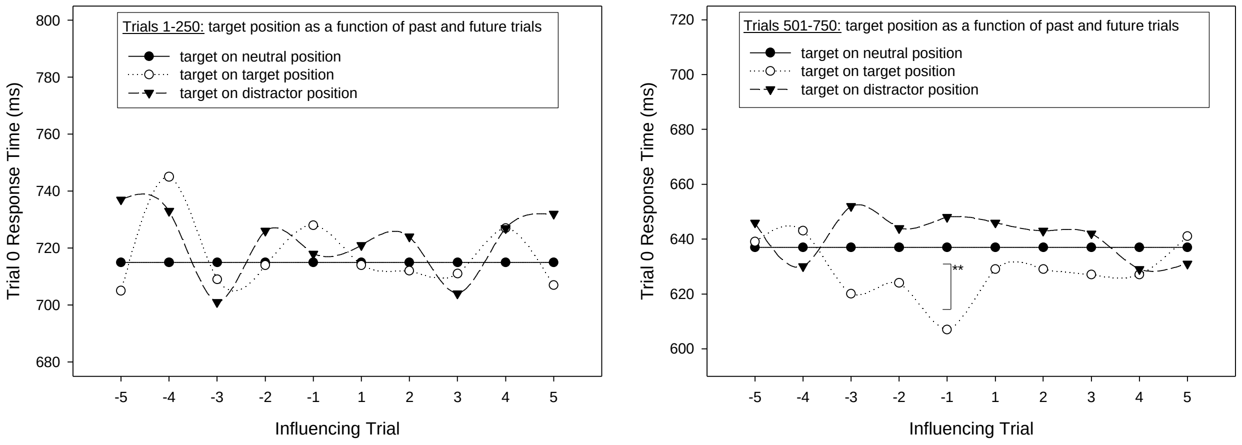

Figure 6. Experiment 2: Mean correct RTs to targets on trial *N* presented at neutral (filled circles), target (open circles), and, respectively, distractor locations (triangles) on previous trials *N-j* or subsequent trials *N+j* dependent on the amount of practice on the task (left-hand panels: trials 1–250; right-hand panels: trials 501–750). While practice led to a general expedition of RT performance, it selectively enhanced RT facilitation, but not inhibition.

Discussion

In Experiment 2, the locations of the two distractors were varied independently of the target location, to prevent the formation, beyond chance level, of a regular triangular arrangement of the target and distractors (in terms of a near-equilateral triangle). The rationale was as follows: If observers in Experiment 1 had learned to use this regularity to guide their search performance (by placing facilitatory and inhibitory tags to target and distractor locations), then the inter-element distance manipulation in Experiment 2 was expected to diminish, if not entirely abolish, the effects of whether the current target appeared at a previous target or a previous distractor location. Consistent with this expectation, in Experiment 2, there was hardly any evidence of facilitation and no evidence whatever of inhibition when target *N* appeared at previous (*N-1* through *N-5*) target or distractor location, respectively. That is, search performance was not (or at beast only weakly) guided by positional short-term memory in Experiment 2. This implies that observers in the 2-distractor condition of Experiment 1 did exploit (probably implicitly, though semi-strategically) the regular spatial arrangement of the display elements on a given trial to guide their search performance on subsequent trials. [The fact that there was some facilitation, but no inhibition in Experiment 2 may be taken to suggest that, in Experiment 1, the regular positioning of the distractors relative to the target was exploited to assign inhibitory tags.]

The (non-) findings of Experiment 2 argue strongly against the view that positional ‘priming’ (in particular, inhibitory ‘priming’) in visual search is based on a passive, non-‘strategic’ memory mechanism that affects all display locations equally, regardless of the elements’ spatial relations. Rather, the present results not only suggest that observers can learn to exploit the spatial arrangement of the display stimuli (provided that it is simple/regular and consistent), but also that the formation of the memory underlying positional priming is critically dependent on this arrangement (this appears to apply more unequivocally to inhibition than to facilitation).

Clear facilitation (extending back to trial *N-5*) was observed only in Experiment 1, when both the target and the distractor locations were repeated on successive trials (rather than just the target location alone, as in Experiment 2). Likewise, inhibition was found only in Experiment 1, when the current target appeared at a previous distractor and one current distractor at a previous target location. In contrast, there was no evidence of inhibition in Experiment 2, when the current target appeared at a previous distractor location, while one or both distractors appeared at previously empty locations. This may suggest that a reciprocal relationship between distractor and target locations on successive trials is crucial for observing both facilitation and inhibition (e.g., Kristjánsson, Wang, & Nakayama, 2002).

However, this suggestion is more descriptive rather than explanatory. Alternatively, inhibitory priming might depend on the distractor locations being defined in terms of a consistent (regular) relation to the target location (as was the case in Experiment 1). If this is not the case (as in Experiment 2), distractor locations may simply not be allocated any inhibitory tags, possibly because it is too demanding to permanently re-compute and store the (ever changing) relations of the distractor locations with reference to the target location. Evidence for this account is that, first, there was at least a measure of facilitatory priming (that increased with practice of the task) in Experiment 2 (i.e., facilitatory priming is, at least to some extent, independent of the reciprocity relationship); and, second, that distractor locations, in contrast to the target location, are unlikely to be explicitly (attentionally) analyzed, that is, distractor locations are determined secondarily with reference to the target location.

The proposal that stimulus arrangement plays an important role in priming is in line with a number of recent studies that have demonstrated short- and long-term effects of the ‘search context’ on response times (e.g., Chun & Jiang, 1998; Karni & Sagi, 2001; Kristjánsson, Wang, & Nakayama, 2002; McCarley & He, 2001; Wang, Cavanagh, & Green, 1994; Wang, Kristjánsson, & Nakayama, 2001). For example, Wang et al. (2001) have pointed out the role of ‘mid-level grouping’, that is, perceptual organization in visual search (besides the roles of bottom-up and top-down processes) – in contrast to current models of visual search that have tended to underrate such organizational processes (Duncan & Humphreys, 1989; Treisman & Gelade, 1980; Treisman & Sato, 1990; Wolfe et al., 1989; Wolfe, 1994). Wang et al. went on to show that priming in singleton (conjunction) search could lead to a dramatic reduction in responses times on both target-present and -absent trials. Because facilitation was found not only for the repetition of the target, but also for that of the distractors features, Wang et al. suggested priming result from expedited grouping of repeated distractors, which, in turn, could facilitate the discernment of a (present) target against the homogeneously grouped distractors. [Note though that, as assumed by Duncan and Humphreys as well as others, grouping of ‘similar’ display elements is possible even if they are not arranged (‘organized’) regularly. Nevertheless, the possibility remains that regular arrangements reinforce groupings via Gestalt formation (which was however not investigated by Wang et al., 2001).]

The results of Experiment 2 are in line with the importance of such ‘mid-level perceptual organization’ processes: when these were prevented (or made hard) by randomizing the organizational ‘context’ frame (which would have forced observers to re-compute the spatial relations among the target and distractor elements on each trial), the inhibitory cross-trial priming effects were abolished and the facilitatory effects substantially diminished [3].

Finally, it is important to point out that, although the pattern of priming effects reported by Maljkovic and Nakayama (1996) was replicated, it applies only to a very special case: displays with one target and two distractors arranged in a regular triangular configuration. Furthermore, and connected with this, priming (in particular, inhibitory priming) effects were the weaker the faster the overall RTs, that is, the more efficiently the target popped out amongst the distractors. This suggests that positional priming effects play an important role only when the search is relatively inefficient, in which case priming effects may contribute to optimizing search performance.

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[3] There may be a somewhat different explanation for the (non-) findings of Experiment 2. Christie and Klein (2001) reported inhibition of target position when the target’s location could not be predicted by the arrangement of the search display, even when the target appeared at the location of a target on a previous trial. Christie and Klein took this finding to suggest that (instead of inhibitory priming) IOR affected the previous target as well as the distractor locations, leading to RT disadvantages for the current target location. It is therefore conceivable that both IOR and (facilitatory) priming were operating in Experiment 2, but that IOR came to the fore, dominating priming. This dominance may simply have ‘masked’ facilitation for the repeated target location. However, if IOR had indeed been operating in Experiment 2, there should have been evidence of inhibition for targets appearing at previous distractor locations (in fact, distractor location IOR and inhibitory priming should have had additive effects). The fact that there was no inhibition suggests that IOR would have played at most a marginal role in Experiment 2. Thus, the most probable explanation for the results of Experiment 2 is that inhibitory priming was not operating in this experiment.]

General Discussion

Inhibition of distractor locations was observed only when there were two distractors in the display that were regularly positioned relative to the target location (Experiment 1), but not when their positioning was random/irregular (Experiment 2). In contrast, repetition of the target location yielded facilitation, relatively independently of the number of distractors (Experiment 1) and their positioning (after some practice, facilitation was manifest even with random/irregular positioning; Experiment 2). Furthermore, the relevant conditions (see above), facilitation was found to be quite robust (especially after practice) and enduring (from trial *N-5* through trial *N-1* onto trial *N*; Experiment 1); in contrast, inhibition was more short-lived (mainly from trial *N-1* onto trial *N*; Experiment 1). No evidence of facilitatory or inhibitory effects on RT were found when the orientation of the target (and, associated with it, the response) was repeated/changed (Experiments 1 and 2), suggesting that both facilitation for target locations and inhibition for distractor locations are linked to the defining, rather than the to-be-reported, target feature. Finally, no evidence of inhibition and little evidence of facilitation (the latter emerged only after extended practice) was found when the distance between the target and distractor locations changed randomly across trial sequences (Experiment 2).

Implications for the nature of priming of positions in visual search.

Experiment 1 revealed evidence for both facilitation and inhibition only in the case of three display elements (the target plus two distractors). In contrast, previous studies (e.g., Phillips, 1974; Yantis & Johnson, 1990; Burkell & Pylyshyn, 1997; Jiang et al., 2004) have pointed to a larger capacity of VSTM, of at least four elements/locations. The differential capacity estimates suggest that single-trial memory and cross-trial priming have different spatial attributes.

In studies that have examined the spatial and temporal of single-trial memory, memory performance was typically found to be determined by at least two parameters: (i) the number of elements presented and (ii) the time between successively presented elements. Usually, observers can memorize four to eight elements with high accuracy within the first 600 to 2,000 ms after the appearance of a test display (Phillips, 1974) or the onset of a subset of display elements (Jiang et al., 2004). However, when investigating trial-to-trial priming, observers' performance is found to be affected by how many times feature-specific stimulus attributes (e.g., position, color, orientation, response etc.) that are repeated on successive trials. Observers show benefits in RT when the current target feature is the same as that in (the 5 to 8) preceding trials (Horowitz, 1995; Maljkovic & Nakayama, 1994, 1996, 2000), and they show costs when the target-defining feature is changed (e.g., when a previous distractor feature now defines the target).

Concerning the spatial characteristics of cross-trial priming, the present results suggest that the capacity of the memory system underlying positional facilitation and inhibition is to be limited to at most three elements/locations. Moreover, facilitation was revealed to be relatively independent of the number (and the regularity of arrangement) of presented elements, suggesting that distinctive types of cross-trial memory are responsible for the priming of target and distractor locations, respectively.

Experiment 2 revealed the formation of positional – in particular, inhibitory – priming with 3-element displays to be dependent on the regularity of the target and distractors' spatial arrangement across sequences of trials. When the separations between the target and the distractors locations changed randomly across trials, evidence of facilitatory priming emerged only after extended practice, whereas no evidence was found at all for inhibitory priming. This qualifies Maljkovic and Nakayama's (1996) work, who characterized cross-trial priming to be rather 'primitive' (i.e., as passive, automatic, not top-down penetrable). While Maljkovic and Nakayama (1996) may be right in considering priming to be "a simple storage of valence" (p. 989), in all of their experiments, the spatial arrangement of the stimuli (target plus 2 distractors) was regular and therefore well predictable (as was the case in the present

Experiment 1). The present results would therefore argue that not only the salience of the target relative to the distractor features, but also the simplicity and predictability of stimulus locations should be taken into consideration in any account of positional cross-trial priming.

Given the more robust evidence for facilitatory priming (even with irregular spatial arrangements), it appears that the allocation and storage for negative “valences” or inhibitory tags is governed by a consistent (configural) spatial frame that is centered on the target location (positive valence/facilitatory tag); that is, inhibitory tags are assigned to other-than-target locations within a fixed reference frame: an equilateral triangular element configuration. The same may apply to slightly more complex arrangements with one target and three distractors, in which case a regular square/diamond reference frame would be used (there was some evidence of inhibitory priming after practice with regular 3-distractor displays in Experiment 1). However, with this more ‘complex’ spatial configuration, the allocation of inhibitory tags is less efficient, and it breaks down completely when displays contain five or more distractors. The reason for this breakdown may be that the reference frame required becomes too complex to permit locations to be tracked efficiently across trials. With 2-distractor/3-element displays, tracking may well be aided by the apparent movement (i.e., rotation around the center) of the triangular frame from one trial to the next. Observers did report that they experienced the trial-to-trial transitions in this manner; and there is evidence that such apparent movement of configurally organized display elements can become stronger phenomenally as a function of practice (e.g., Müller & von Mühlenen, 1996), explaining the practice effects in the present experiments. However, with more complex displays, organized ‘movement’ (rotation) of the whole display configuration becomes harder to discern phenomenally (observers did not report seeing any), so that perhaps only the target location is tracked across trials. This would explain the presence of temporally extended facilitatory priming even with more complex (regular and irregular) element arrangements.

Recently, Hillstrom (2000) suggested that repetition effects in visual (singleton) search result from a single episodic-memory mechanism (see also Neill et al., 1992) which stores information about the features in a given display and about which features were prioritized relative to others (by both bottom-up salience or top-down selection) in the search process. She proposed that the processing of (target) features is expedited by the retrieval of relevant memory traces from previous trials and that the more recent the storage of a memory trace is, the stronger it will (positively) affect visual search. When a trial is dissimilar to a previous one in terms of attentional characteristics, new memory traces will have to be set up and response times will increase correspondingly. The results of the present experiments are generally consistent with this proposal, but qualify the idea of a positional episodic-memory mechanism in three ways. First, the episodic-memory traces are likely to consist of two distinct (but probably linked) types: one representing target and one distractor locations. Second, the positional capacity of the memory appears limited to three (or at most four) spatial locations/elements (with target and distractor representations linked within a simple, regular spatial frame). Third, the encoding and/or retrieval of memory traces is not simply determined by the salience of features and/or top-down attentional signals, but also, critically, by the element configuration (the search context).

In summary, several conclusions can be drawn from the pattern of results found in Experiments 1 and 2: (1) Trial-to-trial priming of target and distractor locations is capacity-limited to three (or at most four) spatially distributed elements/locations. (2) The memory underlying positional priming consists of two distinct types, one responsible for target and one for distractor locations. (3) Positional priming is based on the prioritization/non-prioritization of search feature-related, rather than response feature-related, information of the display elements. (4) Regularity (predictability, simplicity) of the configural arrangement formed by the display elements is a critical factor in the formation of positional (at least inhibitory) priming.

Concerning point (3) above, the present study did not shed much light on the role of the repetition of target- (and, by implication, distractor-) defining features for positional priming. Although repetition/change of target- and distractor-defining features was a variable in Experiments 1 and 2, the numbers of observations were too few to permit the positional analyses reported in the present study to be broken down further. Therefore, further work is required to tell whether and how positional and search-feature related priming effects interact (e.g., are positional priming effects dependent on, or at least enhanced by, repetition of the target-defining features?).

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Chapter 3 – Cross-trial priming in visual search for singleton conjunction targets: Role of repeated target and distractor features

Abstract

Kristjánsson et al. (2002) demonstrated that visual search for conjunctively defined targets can be substantially expedited (‘primed’) when target and distractor features are repeated on consecutive trials. Two experiments were conducted to examine whether the search reaction time (RT) facilitation on target-present trials results from repetition of target-defining features, distractor features, or both. The experiments used a ‘multiple conjunctive search paradigm’ (adapted from Kristjánsson et al., 2002), in which the target and distractor features were varied (i.e., repeated) independently of each other across successive trials. The RT facilitation was numerically largest when both target and distractor features were repeated, but not significantly larger than that when only distractor features were repeated. This indicates that cross-trial priming effects in conjunctive visual search result mainly from the repetition of distractor, rather than target, features.

Introduction

What is real? This question has concerned philosophers from the beginning of recorded history. The materialist would answer that it is only the world of physical objects and events which exists, subjective awareness is just a special property of the brain, and the brain itself is a physical object. In contrast, the idealist would answer that all we can be certain of is that we experience the world. Therefore, what is real is subjective consciousness, that is, our ideas about the world and not the physical world as such.

Today it is clearly evident that the world as described by physics and the perceived world are qualitatively different. When considering, for instance, the perception of color, the physicist refers to varying wavelength, whereas we experience hues such as red, green, etc. Thus, rather than asking the philosopher for what is real, it would be more beneficial to ask how we obtain valid knowledge about the outer world – a question to which an important answer was contributed by Treisman and Gelade (1980) with their *Feature Integration Theory* (FIT).

FIT characterizes object perception as a two-stage process. At the first, 'preattentive' stage, the basic perceptual features of objects (e.g., color) are coded by dimension-specific modules of analyzers operating across the visual field. Spatiotopic feature maps are formed by each module, registering an object's feature value(s) within the respective dimension (e.g., red, green, etc. within the color module). At the second stage, spatial attention focuses on a position within a master map of locations (which signals where there are registered features within the field, but not their individual values) to retrieve and combine, within and across dimensions, the various features recorded at that position in the feature maps. This leads to the creation of a temporary object representation referred to as an 'object file', which can be used to access stored object knowledge for object recognition).

FIT proposes two distinct types of search behavior, depending on whether the *target* object to be detected in a visual search display is defined by a unique single feature in a given dimension (e.g., the only red element amongst blue elements) or a unique conjunction of features (e.g., the only red and vertical element amongst red horizontal and blue vertical elements). In a single-feature search, activity from a single feature map will signal the presence of the target, enabling it to be detected rapidly and independently of the number of display elements. This type of search behavior is referred to as *parallel*. In contrast, in feature conjunction search, a serial, focal-attentional inspection of element locations on the master map is necessary in order to bind the features together correctly, which leads to search RTs that increase linearly with the number of elements [1]. This type of search is referred to as *serial*.

However, subsequently to the original proposal of FIT, a number of findings were reported that challenged the strong assumption of a dichotomy between serial and parallel search processes. One finding was that of *subset search* (e.g., Egeth, Virzi, & Gabart, 1984; Bacon & Egeth, 1997; Friedman-Hill & Wolfe, 1995; Kaptein, Theeuwes, & van der Heijden, 1995), that is, significantly facilitated search for conjunctively defined targets (e.g., a red vertical target amongst red horizontal and blue vertical targets) when observers could effectively limit their search to a subset of the display elements (e.g., the red elements; amongst these, the target is the only vertical element, i.e., effectively defined by a unique orientation feature).

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[1] Assuming random search (without re-inspection of already searched locations), then, statistically, the target is detected after having searched through about half the locations on ‘present’ trials (self-terminating search); in contrast, to rule out target presence on ‘absent’ trials, all locations would have to be searched (exhaustive search). This type of search behavior would give rise to a target-present : -absent RT slope ratio of 1:2.

Thus, many conjunction searches have been found to produce relatively shallow, or even flat search RT slopes (typically associated with parallel search), such as: search for targets defined by shape and binocular disparity (Enns & Rensink, 1991; He & Nakayama, 1992; Ramachandran, 1988); by color and direction of motion; by color and binocular disparity; by size, spatial frequency, and contrast (Nakayama & Silverman, 1986); by shape and direction of motion (Driver, McLeod, & Dienes, 1992; Kingstone & Bischof, 1999; von Mühlenen & Müller, 2001); and by color and orientation (Wolfe, Cave, & Franzel, 1989; Kaptein et al., 1995; Wang, Kristjánsson, & Nakayama, 2001; Kristjánsson, Wang, & Nakayama, 2002).

Several mechanisms have been proposed to account for these discrepant findings (in relation to original FIT). For example, revised FIT (Treisman & Sato, 1990) assumes inhibitory connections between individual feature maps and the master map of locations. If the target and distractor (i.e., non-target) features are known in advance, locations on the master map linked with distractor features can be actively inhibited, thereby enabling efficient search. In contrast, Guided Search (Wolfe, Cave, & Franzel, 1989; Wolfe, 1994) assumes facilitation of the target-defining features, rather than inhibition of distractor features. According to this model, at the preattentive stage, dimension-specific *saliency maps* are computed (based on dimensional feature maps), each map representing, for each element location, the total difference in feature values to other element locations within a particular dimension. The saliency maps for each dimension are subsequently summed onto an overall activity or saliency map, which guides focal attention to locations exhibiting the highest overall saliency (activity). If the target features are known in advance, top-down enhancement of target-feature coding leads to higher overall activation of items sharing target features on the dimensional saliency maps and, as a result, the overall saliency map. Hence, it is more likely that focal attention will be guided towards the target location (or, at least, the locations of items sharing target features), and search will be efficient.

The *Attentional Engagement Theory* (AET; Duncan & Humphreys, 1989; 1992) proposes a somewhat different explanation for efficient (conjunctive) search. AET differs fundamentally from FIT (and Guided Search) in that it assumes no processing limitations of the preattentive stage. Rather than ascribing to attention a critical role in the binding of features into objects, the preattentive processing stage produces integrated, *structural units* as output representations. These units are assumed to be organized hierarchically, with the highest level of the structural units providing a representation of the visual scene (e.g., a top-level unit representing the letter T will be encompass lower-level units representing a horizontal and vertical line, respectively).

Further, the units are segregated by the principles of similarity grouping, that is, elements sharing one particular feature (e.g., orientation) at a particular spatial scale will form one unit. With respect to visual search, grouping involves not only (similarity) relations between targets and distractors (T-D similarity), but also among different distractors (D-D similarity). The interaction between these two factors determines search efficiency: when T-D similarity is low, search is efficient, irrespective of D-D similarity; when T-D similarity is high, search efficiency is strongly dependent on D-D similarity. Hence, rather than making a qualitative distinction between feature and conjunction searches, AET assumes a continuum of search efficiency, which is determined by the strength of the grouping relations among the display elements.

Cross-trial priming as a mechanism of efficient visual (conjunction) search

Recent work by Maljkovic and Nakayama (1994; 1996; 2000; see also McPeek, Maljkovic, & Nakayama, 1999) has shown that the repetition of the target features can improve search efficiency. In a *pop-out* search task, the authors found short-term priming for both the color and the position of the target (Maljkovic & Nakayama, 1994; 1996); that is, RTs were expedited when the color and, respectively, the position of the target was repeated, relative to the non-repetition of these target attributes. Such RT advantages were evident for the last five to eight trials, and were not found to be subject to voluntary control (Maljkovic & Nakayama, 1994; 2000; but see Müller, Reimann, & Krummenacher, 2003, and Müller, Krummenacher, & Heller, 2004, for conflicting evidence).

Further, Kristjánnson, Wang, and Nakayama (2002; Wang, Kristjánnson, & Nakayama, 2001) demonstrated priming in conjunctive visual search. They used a *multiple conjunctive search paradigm*, in which the target and distractors could change their features in sequences of trials. Participants' task was to detect a uniquely oriented red target, which was presented amongst differently oriented red and similarly oriented green distractors. Thus, on one trial, the orientation of the (red) target could be, say, horizontal and it appeared amongst vertical-red and horizontal-green distractors; but on the next trial, the (red) target could be vertical in orientation and presented amongst horizontal-red and vertical-green distractors. The experiment comprised four major conditions: (1) In the *conjunction condition*, the target never changed its orientation, that is, it was always vertical; as a result, priming was expected to be large, leading to the fastest overall search RTs. (2) In the *switch condition*, the target changed its orientation predictably from horizontal to vertical and vice versa from one trial to the next; search performance was expected to be worse, because the orientation of the target was never repeated (i.e., there was no priming). (3) In the *streak condition*, the target also changed orientation between horizontal and vertical, but its orientation remained constant for longer streaks of trials; as a result, search performance was expected to be better than in the switch condition. (4) In the *random condition,* the target changed its orientation randomly between horizontal and vertical from one trial to the next; again, performance was expected to be superior to the switch condition. The results showed the expected pattern: search RTs were fastest in the conjunction condition, intermediate in the streak and random conditions, and slowest in the switch condition (in terms of the y-intercepts of the functions relating RT to the number of elements in the display). However, when only the last few trials in a streak (trials 6 to 8) were compared to the conjunction condition, search performance showed no quantitative difference between the two conditions. From this, the authors concluded that priming alone can account for the search RT benefits found in the conjunction condition – and, by extension, for efficient conjunctive search in general.

Interestingly, in the streak condition, priming was evident not only on target-present, but also on target-absent trials. This led Kristjánnson et al. to assume that (facilitatory) priming might result from faster perceptual grouping of distractor elements, which, in turn, might lead to faster target-present, as well as -absent, decisions – due to faster discernment of target presence against the background of homogeneous, grouped distractors. However, for target-present trials, Kristjánnson et al. alternatively considered the possibility that facilitatory priming might be the result of the repetition of the target features alone (cf. Maljkovic & Nakayama, 1994; Experiment 8). Applied to their findings, the repetition priming by the (same-oriented) target might have annulled the effect of the repeated distractor orientation, such that the repetition of the (same-oriented) distractors would have had only a marginal effect (see Kristjánnson et al., p. 47).

However, there is one shortcoming with this proposal. Because both the orientation of the target and, together with this, the orientation of the distractors were repeated in the streak condition, Kristjánsson et al. were unable to dissociate the effect of repeated target orientation from that of repeated distractor orientation and, thus, the mechanism(s) of facilitatory priming as target- versus distractor-based. The present experiment was designed to resolve this issue: Target and distractor features were varied independently of each other across consecutive trials, permitting the effects of repeated target and, respectively, distractor features on priming in conjunctive visual search to be disentangled.

Given the evidence of facilitatory priming on target-absent trials (Kristjánnson et al., 2002), it seems reasonable to assume that the same, distractor-based priming mechanism is also at work on target-present trials; on the latter, however, an additional, target-based mechanism may come into play as well. [This is more parsimonious than the possibility considered by Kristjánnson et al. that the distractor-based effect is overridden (annulled) by target-based priming on target-present trials.] Therefore, the present experiments sought evidence to what extent facilitatory priming, on target-present trials, is dependent on the repetition of distractor, rather than target, features.

Experiment

The relative contributions of distractor and, respectively, target feature repetition to priming in conjunction search was assessed in two experiments, Experiments 1A and 1B. Both experiments used a ‘multiple conjunctive search paradigm’ adapted from Kristjánnson et al. (2002): Observers were presented with displays of colored bar stimuli (see Figure 1 for an example) and had to discern the presence/absence of a singleton target defined by a conjunction of color (constant across trials) and bar orientation (variable across trials). In more detail, the target was a uniquely oriented red target, which could change its orientation from one trial to the next. The distractors were red and green in color. Red distractors were of different and green distractors of the same orientation as the target.

Experiments 1A and 1B differed in the number of possible target (orientation) alternatives, in order to examine a possible influence of target uncertainty on target-based priming effects (for rationale, see below). In Experiment 1A, the orientation of the (red) target was either horizontal or vertical; that is, there were two alternative target orientations. If the target was horizontal, the green distractors were horizontal and the red distractors were either vertical or oblique (all tilted by 45° to either the left or the right, respectively). If the target was vertical, the green distractors were vertical and the red distractors were either horizontal or oblique. In Experiment 1B, the orientation of the target was either horizontal, vertical, or oblique (45° left- or right-tilted, respectively); that is, there were four alternative target orientations. If the target was horizontal or oblique, the green distractors were horizontal or oblique, respectively, and the red distractors were vertical; if the target was vertical or oblique, the green distractors were vertical or oblique, respectively, and the red distractors horizontal in orientation.

Given the variability of element orientation across trials, the following cross-trial transition conditions were realized in both Experiments 1A and 1B: repetition of (1) both target and (red) distractor orientation on consecutive trials; (2) target orientation alone; (3) (red) distractor orientation alone; and (4) neither target nor (red) distractor orientation. [This is in contrast with Kristjánnson et al., who had realized only conditions (1) and (4)]. Thus, by varying target and (red) distractor repetition independently of each other, it became possible to determine the relative strengths of target- and distractor-based priming effects on target-present trials (and compare these with distractor-based priming effects on target-absent trials).

The logic of this determination was as follows. Priming was assessed by comparing target detection RTs in each of the three 'repetition' conditions (i.e., repetition of either target orientation only, or distractor orientation only, or both) against the RTs in the baseline condition in which neither the target nor the distractor orientation was repeated. It seemed reasonable to expect the facilitation (relative to the baseline) to be at maximum when both target and distractor orientation are repeated (especially if target repetition were making a contribution over and above that of distractor repetition [in the most simple case, if both types of repetition were having additive effects]). This (expected) maximum priming effect could then be compared and contrasted with the effects when either target or distractor orientation were repeated alone.

If priming is due to the repetition of the target orientation alone, the facilitatory effect of the repetition of the (same-oriented) target alone should be equivalent to the maximum priming effect. In contrast, if priming is determined by the repetition of distractor orientation alone, the facilitatory effect of the repetition of the (same-oriented) distractors should equal to the maximum priming effect. However, if facilitatory priming is dependent on the repetition of both target and distractor orientation, a substantial RT advantage is expected only when both target and distractor orientation are repeated.

Conceivably, target-based priming effects might depend on the number of possible (alternative) target orientations (target uncertainty), and distractor-based effects might depend on the number of possible (red) distractor orientations (distractor uncertainty). For example, the greater the number of target alternatives, that is, the greater the amount of information gained by detecting a particular target (orientation) on a given trial, the greater the priming effect. To examine for possible effects of target uncertainty, modulating target-based priming effects, and of (red) distractor uncertainty, modulating distractor-based effects, the number of alternative target and (red) distractor orientations was varied between Experiments 1A and 1B: In Experiment 1A, there were 2 target and 4 (red) distractor alternatives; conversely, in Experiment 1B, there were 4 target and 2 (red) distractor alternatives. Thus, if priming effects are modulated by uncertainty, one might have expected target-based priming to be greater in Experiment 1B than in Experiment 1A, and distractor-based priming to be greater in Experiment 1A than in Experiment 1B.

Method

Participants. Ten observers participated in Experiment 1A (seven females, three males; ages ranging from 21 to 43 years), and ten different observers in Experiment 1B (four females, six males; ages ranging from 22 to 39 years). All observers reported normal or corrected-to-normal vision. They were paid at a rate of Euro 8.00 per session.

Apparatus. The experiments were conducted in a dimly lighted laboratory, to minimize reflections on the monitor. Stimulus presentation and RT measurement were controlled by a standard PC (a 75 MHz Pentium I). Stimuli were presented on a 17-inch color monitor (at a frame rate of 60 Hz), with a resolution of 640 x 480 pixels. Observers viewed the monitor from the distance of approximately 60 cm, maintained by the use of a chin rest.

They responded ‘target-present’ and ‘-absent’ by pressing the right and left buttons of a serial Microsoft mouse, with track ball removed to improve timing accuracy (Segalowitz & Graves, 1990).

Stimuli. The stimuli, which were modelled after those used by Kristjánsson at al. (2002), are depicted schematically in Figure 1.

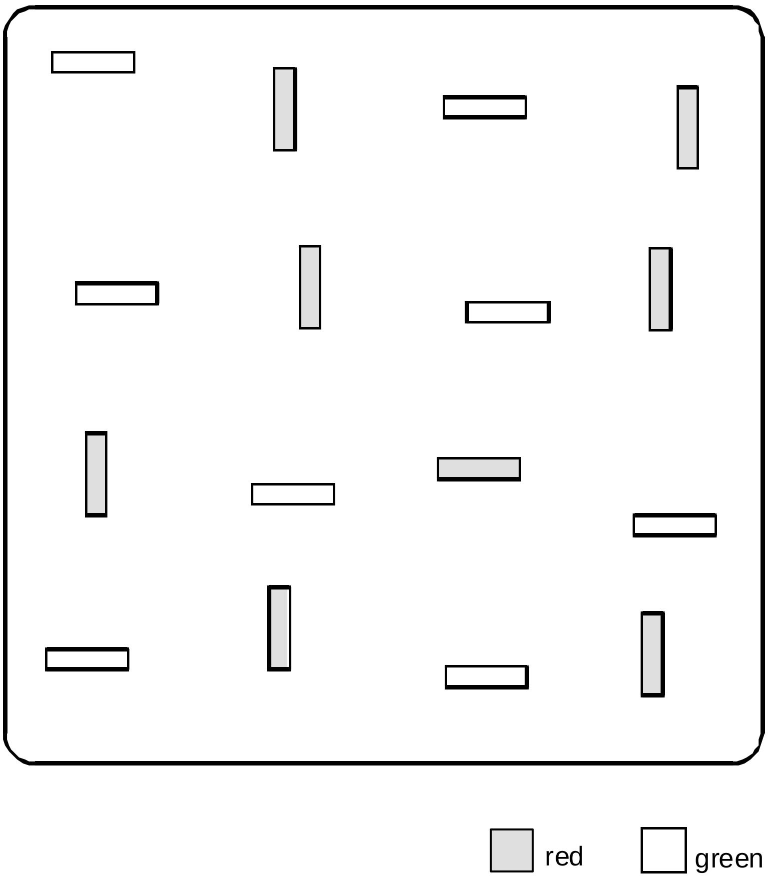

Figure 1: Example of a search display (of size 16 elements) used in Experiments 1A and 1B. Participants’ task was to detect a uniquely oriented red target bar, which was presented amongst (relative to the target) different-oriented red distractors and same-oriented green distractors. (In the figure, the target is the only red-horizontal bar.)

Each search display comprised of either 4, 8, or 16 oriented bar elements which were randomly scattered across the cells of an invisible 4 x 4 matrix. The size of the matrix was 14.9° x 14.9° of visual angle, and the size of the bars was 1.7° x 0.4° (whether they were oriented horizontally, vertically, or obliquely [45° left- or right-tilted). The arrangement of the bars within the display matrix was slightly jittered, with the horizontal and vertical distances between adjacent bars varying between 1.3° and 2.7°. The bars were either red (8.9 cd/m²) or green (9.4 cd/m²). The background was essentially black and had a luminance of 0.5 cd/m². The white fixation cross, presented at the start of a trial in the display center, was 0.5° x 0.5° in size, with a luminance of 13.7 cd/m². Error feedback was given by a 1000-Hz tone sounded for 100 ms.

Design and procedure. Figure 2 presents all possible target and distractor orientations used Experiments 1A (upper panel) and 1B (lower panel). The target, if present, was always a red bar and could change its orientation across trials. The distractors were red and green bars and changed their orientations in accordance with the target.

In Experiment 1A, a horizontal-red target appeared amongst horizontal-green and either vertical (10.0% of all trials), left-tilted (10.0%), or right-tilted (10.0%) red distractors; and a vertical-red target appeared amongst vertical-green and either horizontal (10.0%), left-tilted (10.0%), or right-tilted (10.0%) red distractors. In the absence of a target, there were either horizontal-red and vertical-green distractors (6.6%), or vertical-red and horizontal-green distractors (6.6%). The red distractors could also be left-tilted, with either horizontal-green or vertical-green distractors (each 6.6%); or they could be right-tilted, with either horizontal-green or vertical-green distractors (each 6.6%).

In Experiment 1B, a horizontal-red target was presented amongst horizontal-green and vertical-red distractors (10.0% of all trials). The target could also be vertical-red amongst vertical-green and horizontal-red distractors (10.0%); further, if the target was left-tilted, it was presented amongst left-tilted green and either horizontal-red or vertical-red distractors (each 10.0%). Finally, the target could also be right-tilted, presented amongst right-tilted green and either horizontal-red or vertical-red distractors (each 10.0%). On target-absent trials, horizontal-red distractors were presented with either vertical, left-, or right-tilted green distractors (each 6.6%), or vertical-red distractors were presented with either horizontal, left-, or right-tilted green distractors (each 6.6%).

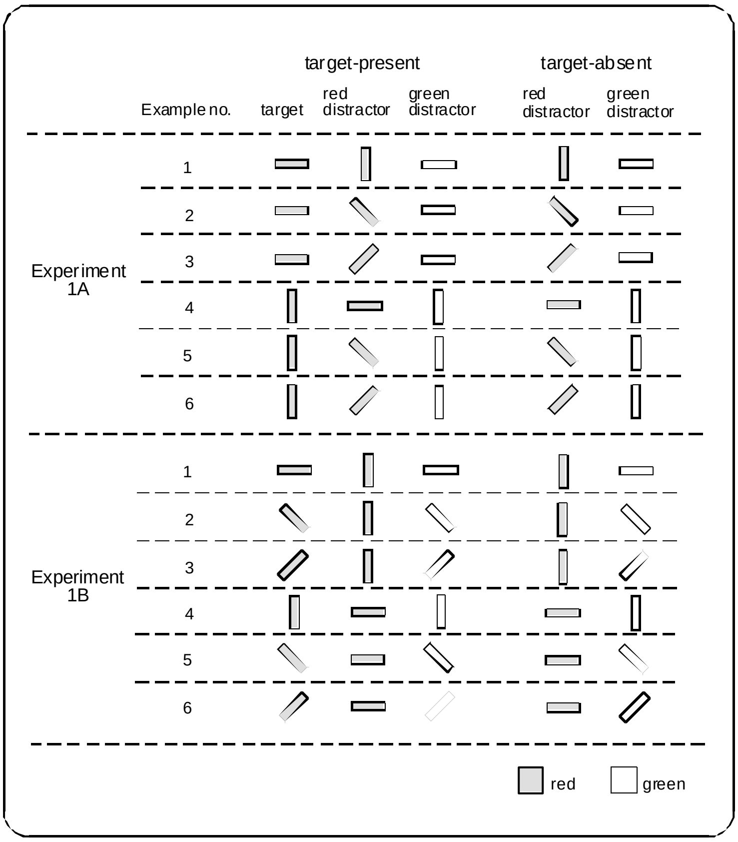

Figure 2: Figure 2 presents all different target and distractor orientations in Experiment 1A (upper-panel) and Experiment 1B (lower-panel). In Experiments 1A and 1B, the red target and the red distractors could change their orientations independently of each other on consecutive trials. In Experiment 1A, the red target could be horizontal in orientation amongst horizontal-green and either vertical-red or oblique-red (all 45° left- or right-tilted, respectively) distractors; or the red target could be vertical amongst vertical-green and either horizontal-red or oblique-red distractors. In the absence of a target, horizontal-green distractors were presented together with either vertical-red or oblique-red distractors; or the display consisted of vertical-green and either horizontal-red or oblique-red distractors. In Experiment 1B, the target was either horizontal-red (with horizontal-green and vertical-red distractors), vertical-red (with vertical-green and horizontal-red distractors), or oblique-red (with oblique-green and either horizontal-red or vertical-red distractors). In the absence of a target, horizontal-green distractors appeared together with vertical-red distractors; vertical-green distractors appeared together with horizontal-red distractors; or oblique-green distractors appeared together with either horizontal-red or vertical-red distractors.

Experiments 1A and 1B consisted of 2160 experimental trials each, that is, 360 trials for each display size (4, 8, 16 elements) x target (present, absent) combination. Each display size condition consisted of 360 mixed pairs of trials, representing 6 times all 36 possible cross-(consecutive-)trial contingencies on target-present trials (e.g., horizontal-red target amongst horizontal-green and vertical-red distractors followed by horizontal-red target amongst horizontal-green and right-tilted red distractors), and 4 times all 36 cross-trial contingencies on target-absent trials (e.g., horizontal-green and vertical-red distractors followed by vertical-green and horizontal-red distractors), with each contingency realized ten times. Note that the target-present : -absent trial ratio was 60% : 40%, in order to take account of the greater number of major cross-trial transition conditions on target-present than on -absent trials (4 vs. 2; see below).

Since the last trial of a pair formed the first trial of the next pair, after randomization, each type of contingency should be represented twenty (rather than just ten) times in each display-size condition. However, for the same reason, a target-present trial could also follow a target-absent trial and vice versa. Because the aim of the study was to analyze the effects of repeated target and, respectively, distractor orientations, which required pairs of target-present and pairs of -absent trials, such trials (target-present trials following target-absent trials, target-absent trials following target-present trials) were discarded from further analysis (about 25% of all trials). Of the remaining trials, 60% were target-present and 40% -absent trials. Thus, each of the 36 different cross-trial contingencies on target-present trials was repeated at least six times and each of the 36 contingencies on target-absent trials was repeated at least four times.

The 36 different pairs of target-present trials could be classed in terms of four major conditions: *sTsD*, that is, same-oriented target, same-oriented red distractors (6/36 of all cross-trial contingencies); *sTdD*, that is, same-oriented target, different-oriented red distractors (Experiment 1A: 12/36; Experiment 1B: 4/36); *dTsD*, that is, different-oriented target, same-oriented red distractors (Experiment 1A: 4/36; Experiment 1B: 12/36); and *dTdD* , that is, different-oriented target, different-oriented red distractors (14/36). The 36 different pairs of target-absent trials could be classed in terms of two major conditions: *sD*, that is, same-oriented red distractors (Experiment 1A: 10/36; Experiment 1B: 18/36), and *dD*, that is, different-oriented red distractors (Experiment 1A: 26/36; Experiment 1B: 18/36).

At the beginning of a trial, a fixation cross was presented in the center of the monitor for 800 ms, followed by a blank interval of 200 ms. Thereafter, the search stimuli appeared and remained visible until participants responded target-present or -absent by pressing the right or left button of the computer mouse with the index finger of their right or left hand, respectively. When an observer had made an incorrect response (target miss or false alarm), he/she was alerted to his/her error by a brief computer-generated ‘beep’. The inter-trial interval was 1000 ms following correct-response trials and 2000 ms after an error signal. Within each experiment, all different cross-trial contingencies on target-present and -absent trials were presented in randomized order. The number of display elements remained the same within a block, but was varied randomly across blocks.

Experiments 1A and 1B were both run in two sessions, separated by a break of at least one hour. Each session consisted of 12 blocks of 5 (unrecorded) practice trials plus 85 experimental trials. Before the beginning of the experiment, observers performed a practice session of 75 trials (data not recorded).

Observers were instructed to respond as fast and as accurately as possible to the presence versus absence of the uniquely oriented red bar.

Results

For both experiments, the data from the practice block and the first five warming-up trials of each experimental block were excluded from analysis. For each experimental condition (display size x target), RTs outside the range of ?2.5 standard deviations (SD) from the mean were discarded as ‘outliers’ (overall, 2.8% of trials in Experiment 1A, 2.6% in Experiment 1B). Error-response trials were also excluded from the analysis (2.8% and 2.9% of all trials in Experiment 1A and Experiment 1B, respectively; for further details, see ‘accuracy’ results below). When examining for the effects of repetition, the current trial may have been influenced by the preceding trial or it may have influenced the subsequent trial. Therefore, responses on trials that preceded or followed an erroneous response were not analyzed. In other words, repetition effects were analyzed only for two consecutive trials on which the responses were correct.

The results are presented in the following sections, first for the overall RT and accuracy performance, followed by the theoretically important effects of cross-trial transition for target-absent (sD, dD) and -present trials (sTsD, sTdD, dTsD, dTdD), respectively.

Overall RT performance. Figure 3 presents the group mean correct RTs, along with the error rates, in Experiment 1A (left-hand panel) and Experiment 1B (right-hand panel) as a function of display-size, separately for target-present and -absent trials. RTs were examined by a mixed-design analysis of variance (ANOVA) with three factors: experiment (1A, 1B; between-subject factor), display-size (4, 8, 16 elements), and target (present, absent). This ANOVA revealed the main effects of display size [$F(2,18) = 47.82$; $p < .01$; $MS_E = 9927$] and target [$F(1,9) = 13.05$; $p < .01$; $MS_E = 6127$] to be significant; all other effects were non-significant. RTs increased with increasing display size (main effect of display size: 622, 710, and 838 ms for 4-, 8-, and 16-element display, respectively), and target-present RTs were faster than -absent RTs (697 vs. 749 ms). Importantly, there were no effects of experiment [main effect: $F(1,9) = 0.34$; $p=.57$; $MS_E = 116{,}586$]), indicating that similar search processes operated in both Experiment 1A and Experiment 1B.

Overall response accuracy. Participants’ individual error rates ranged between 1.0 and 4.4% in Experiment 1A, and between 1.6 and 4.1% in Experiment 1B. The individual error rates were also analyzed by a mixed-design ANOVA, with experiment (1A, 1B; between-subject factor), display-size (4, 8, 16 elements), and target (present, absent) as factors. This ANOVA revealed the main effect of display size [F(2,18) = 11.13; p<.00; MS_E = 1.46] and the two-way interaction between display size and target [F(2,18) = 20.78; p<.00; MS_E = 2.82] to be significant. More errors were made when display-size increased (main effect of display size: 2.66, 2.74, and 3.80% for 4-, 8-, and 16-element displays, respectively). However, this effect was due to a moderate increase in error responses on target-present trials (miss rates of 1.35, 2.26, and 4.88% for 4-, 8-, and 16-element displays, respectively), rather than target-absent trials (false-alarm rates of 3.97, 3.22, and 2.73%, respectively), accounting for the display size x target interaction. Thus, overall, there was little indication of the RT display size and target main effects (and the non-significant effect of experiment) being confounded by speed-accuracy trade-offs.

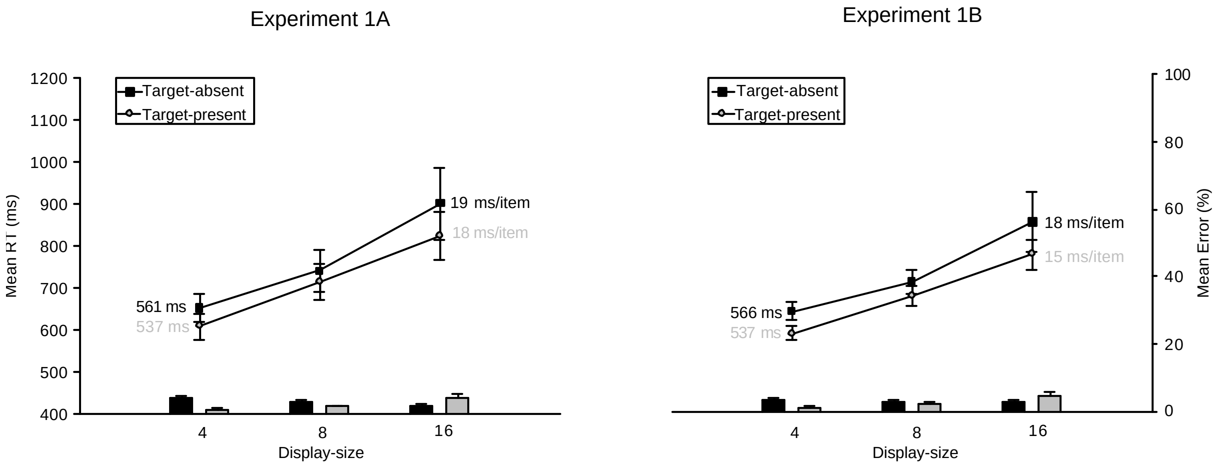

Figure 3: Group mean percentage errors with associated standard errors (compare bars with right axis) and group mean correct response times (RT) with associated standard errors (compare lines with left axis) in Experiment 1A (left-hand panel) and Experiment 1B (right-hand panel) as a function of display-size, separately for target-present and -absent trials. The number to the left of each line represents the y-intercept (in ms), the number to the right the search rate (in ms/element) of the respective RT/display size function.

Cross-trial analysis of target-absent RTs. Table 1 presents, for Experiments 1A and 1B, the group mean correct RTs on target-absent trials as a function of display size, separately for same-orientation (sD) and different-orientation (dD) cross-trial transitions. Further, for each display size condition, the table gives the difference in RT between the sD and dD conditions.

	Experiment 1A						*Experiment 1B*					
Display-size	*4*		*8*		*16*		*4*		*8*		*16*	
Transition	*RT*	DIFF	*RT*	DIFF	*RT*	DIFF	*RT*	DIFF	*RT*	DIFF	*RT*	DIFF
dD	*643*		*730*		*885*		*651*		*719*		*870*	
sD	*616*	27	*689*	41	*820*	65	*623*	28	*691*	28	*827*	43

Table 1: Group mean correct RTs (ms) on target-absent trials in Experiments 1A and 1B as a function of display size (4, 8, 16 elements), separately for same- (sD) and different-orientation (dD) distractor transitions on consecutive trials. Also listed are the RT differences (DIFF) between the sD and dD conditions for each display size condition. Across Experiments 1A and 1B, the repetition of (same-oriented) distractors expedited RTs by approximately 40 ms, relatively independently of the number of display elements.

To examine the effect of repeated distractor orientation, the target-absent RTs were analyzed by a separate mixed-design ANOVA with the factors experiment (1A, 1B; between-subject factor), display-size (4, 8, 16), and transition (sD, dD). The main effect of display size was significant [F(2,18) = 27.29; p<.00; MS_E = 8944)], due to a slowing of RTs with increasing display size (633, 707, and 850 ms for 4-, 8-, and 16-element displays, respectively). Further, there was a reliable main effect of transition [F(1,9) = 24.95; p<.00; MS_E = 890)]: RTs were significantly expedited when the orientation of the red distractors was repeated relative to when it was changed (711 [sD] vs. 750 ms [dD]). No further effects were significant. [Note, though, that there was a non-significant tendency for the RT facilitation due to distractor repetition to increase as a function of display size (transition x display size interaction: F(2,18) = 2.12; .15>p>.10; MS_E = 440); 28, 35, and 54 ms for 4-, 8-, and 16-element displays, respectively).]

Cross-trial analysis of target-present RTs. Table 2 presents, for Experiments 1A and 1B, the group mean correct RTs on target-present trials as a function of display size, separately for repetitions, on consecutive trials, of both target and distractor orientations (sTsD), target orientation alone (sTdD), distractor orientation alone, (dTsD) or neither target nor distractor orientation (dTdD). Further, for each display size condition, the differences in RT are given for the sTsD, sTdD, and dTsD conditions relative to the dTdD (baseline) condition. A mixed-design ANOVA with the factors experiment (1A, 1B; between-subject factor), display size (4, 8, 16 elements), and transition (sTsD, sTdD, dTsD, dTdD) revealed the main effects of display size [F(2,18) = 108.44; p<.00; MS_E = 3757] and transition [F(3,27) = 12.50; p<.00; MS_E = 676] and the display size x transition interaction [F(6,54) = 2.89; p<.02; MS_E = 392] to be significant.

Search RTs increased as a function of the number of display elements (main effect of display size: 588, 684, and 789 ms for 4-, 8-, and 16-element displays, respectively). Further, RTs were fastest in the sTsD (673 ms) and dTsD conditions (674 ms), intermediate in the sTdD condition (692 ms), and slowest in the dTdD-condition (708 ms) (main effect of transition). However, this effect of transition was dependent on the display size (display size x transition interaction): With 16-element displays, search RTs were fastest in the sTsD (768 ms) and dTsD conditions (770 ms), intermediate in the sTdD-condition (793 ms), and slowest in the dTdD condition (828 ms) (Tukey LSD tests revealed the fastest RTs to be significantly faster than the intermediate RTs, and the latter to be faster than the slowest RTs); thus, the ordering was the same as in the transition main effect. However, with 8-element displays, observers responded fastest in the sTsD (671 ms) and dTsD conditions (671 ms), and slowest in the sTdD (693 ms) and dTdD conditions (701 ms). And with 4-element displays, RTs were comparable in all transition conditions (581, 592, 582, and 597 ms in the sTsD, sTdD, dTsD, and dTdD conditions, respectively); nevertheless, the pattern of RTs tended to be similar to those observed with 8- and 16-element displays. [Overall, the RT facilitation resulting from distractor and, to a lesser extent, target repetition increased as a function of display size (facilitation associated with distractor repetition (sTdD condition): 16, 30, and 58 ms for 4-, 8-, and 16-element displays, respectively; facilitation associated with target repetition (sTdD): 6, 8, and 35 ms, respectively), a pattern that was also evident (though non-significant) on target-absent trials.]

	Experiment 1A						*Experiment 1B*					
Display-size	*4*		*8*		*16*		*4*		*8*		*16*	
Transition	*RT*	DIFF	*RT*	DIFF	*RT*	DIFF	*RT*	DIFF	*RT*	DIFF	*RT*	DIFF
dTdD	*605*		*714*		*853*		*589*		*687*		*802*	
sTsD	*582*	23	*686*	28	*787*	66	*580*	9	*656*	31	*749*	53
sTdD	*596*	9	*708*	6	*817*	36	*586*	3	*677*	10	*768*	34
dTsD	*584*	21	*681*	33	*790*	63	*578*	11	*660*	27	*749*	53

Table 2: Group mean correct RTs (ms) on target-present trials in Experiments 1A and 1B as a function of display size (4, 8, 16 elements), separately for repetitions of both target and distractor orientation (sTsD), target orientation alone (sTsD), distractor orientation alone (dTsD), or neither target nor distractor orientation (dTdD) across consecutive trials. Also listed are the RT differences (DIFF) between the dTdD (baseline) and the sTsD, sTdD, and dTsD conditions, respectively. Across Experiments 1A and 1B, the repetition of both target and distractors (sTsD), target alone (sTdD), and distractors alone (dTsD) facilitated responses by approximately 35, 16, and 35, respectively.

Comparison of distractor repetition effects between target-absent and -present trials. To compare the facilitatory effects of distractor repetition between target-absent and present trials, a further mixed-design ANOVA with the factors experiment (1A, 1B; between-subject factor), target (absent, present), display size (4, 8, 16 elements), and transition (sD, dD [i.e., for target present trials, dTsD vs. dTdD]), was carried out. This ANOVA revealed only the main effects of target ($F(1,9) = 8.30$; $p<.02$; $MS_E = 11152$; faster target-present than -absent RTs), display size ($F(2,18) = 56.41$; $p<.00$; $MS_E = 16349$; RT increasing as a function of display size), and transition ($F(1,9) = 33.41$; $p<.00$; $MS_E = 2389$; faster RT for repeated than non-repeated distractor orientation), and the display size x transition interaction ($F(2,18) = 7.88$; $p<.01$; $MS_E = 796$; RT facilitation associated with distractor repetition increasing as a function of display size) to be significant. Importantly, none of the interactions involving target and transition were significant (target x transition interaction: $F(1,9) = .59$; $p>.45$; $MS_E = 404$). That is, the RT facilitation deriving from distractor repetition was not significantly different between target-absent and -present trials (39 vs. 35 ms; the small numerical difference is unsurprising, for two reasons: the target-present RTs were generally faster, by 40 ms, leaving somewhat less room for priming to become fully effective; alternatively, on target-absent trials, the [red] target was replaced by an additional [red] distractor, giving rise to stronger distractor grouping).

Effects of target and, respectively, distractor uncertainty. Although none of the above ANOVAs had revealed an effect of experiment, that is, a factor reflecting variation of target relative to distractor uncertainty (Experiment 1A: 2 target alternatives vs. 4 distractor alternatives; Experiment 1B: 4 target alternatives vs. 2 distractor alternatives), there were some tendencies in the data that are worth mentioning. Doubling the number of target alternatives had no discernible effect on the RT facilitation deriving from target repetition (i.e., the RT difference between the dTdD and sTdD conditions): the overall facilitation was 17 and 16 ms in Experiments 1A and 1B, respectively. However, doubling the number of distractor alternatives tended to increase the RT facilitation deriving from distractor repetition (i.e., the RT difference between the dD and sD [target-absent trials] and dTdD and dTsD [target-present trials] conditions): the overall facilitation was 44 versus 33 ms in Experiments 1A and 1B, respectively, on target-absent trials and 39 versus 30 ms on -present trials. [However, the above ANOVA (see section Comparison of distractor repetition effects between target-absent and -present trials) failed to reveal the experiment x transition interaction to be significant ($F(1,9) = .74$; $p>.40$; $MS_E = 1837$).]

Discussion

The present experiments were designed to examine the mechanisms of facilitatory priming in conjunctive visual search. Participants' task was to detect a uniquely oriented red target item (presented in 60% of all trials) amongst different-oriented red and same-oriented green distractor items. Contrary to standard conjunctive search, where the target and distractor features remain constant throughout the task (feature certainty), the present experiments used a multiple color-orientation conjunction search paradigm, in which both the target and the distractors could (independently) change their orientation features across consecutive trials. Accordingly, the number of orientation alternatives of the target was different to the number of alternatives of the (red) distractors (Experiment 1A: 2 vs. 4, i.e., distractor uncertainty > target uncertainty; Experiment 1B: 4 vs. 2, i.e., target uncertainty > distractor uncertainty). With this manipulation, it was possible to decide (1) whether, and to what extent, facilitatory priming depends on the repetition of both target and distractor orientation, target orientation alone, or distractor orientation alone, and (2) to what extent priming is modulated by the degree of target and distractor uncertainty, respectively.

The analysis of target-absent trials revealed the repetition of the red distractors' orientation (sD) to lead to overall RT advantages of some 40 ms (across all display sizes), relative to the non-repetition of distractor orientation (dD). This effect confirms that facilitatory priming can occur even in the absence of a target (cf. Kristjánsson et al., 2002). On target-present trials, the repetition of both target and distractor orientation (sTsD) expedited responses by, on average, 35 ms, relative to the non-repetition of target and distractor orientation (dTdD). Interestingly, the RT facilitation was not reduced compared to that when only the distractor, but not the target, orientation was repeated (dTsD). In contrast, the facilitatory effect resulting from just the repetition of target, but not distractor, orientation was comparatively small in magnitude (16 ms). This pattern of results makes supports the view that priming in conjunctive visual search is due mainly to the repetition of distractor, rather than target, orientation – in line with previous studies (e.g., Karni & Sagy, 1993).

When distractor orientation was repeated, additional repetition of the target orientation had almost no extra effect; however, when only the target orientation was repeated, there was an effect (but this was less than half that of the repetition of distractor orientation alone). This suggests a non-additive, interactive account of distractor- and target-based priming effects, such that target repetition can only marginally enhance the (almost 'saturated') effect of distractor repetition. The dominance of distractor-based priming may arise perhaps because distractor repetition affords faster perceptual grouping, permitting target presence/absence to be discerned more rapidly (amongst homogeneous, grouped distractors) (cf. Kristjánsson et al., 2002). [Note, though, that 'grouping' is not a necessary assumption to account for distractor-based priming; alternative accounts based on Guided Search, such as that considered by Hillstrom (2000) for target-based priming, are also possible (see General Discussion).]

With reference to the priming mechanisms discussed by Kristjánsson et al. (2002), the present results do not rule out that, on target-present trials, some priming effect does result from the repetition of target orientation. However, they do rule out priming to be dominated by repetition of target orientation. That is, at variance with the possibility considered by

Kristjánsson et al. (2002), the priming resulting from target repetition does not anull that produced by distractor repetition.

Interestingly, while the effect of distractor repetition was independent of the number of display elements on target-absent trials (though there was a tendency for an interaction), on target-present trials, the distractor repetition effect depended on display-size: it was greater (and reliable only) with 16- and 8-element displays. At the first glance, this display size x target interaction might be taken to suggest that priming results from different mechanisms on target-present (e.g., priming resulting from repetition of target orientation) and -absent trials (e.g., priming resulting from repetition of distractor orientation). However, the non-reliable facilitation in the 4-element display size condition (on target-present trials) can equally be explained by assuming that the faster perceptual grouping of distractors and, as a consequence, the faster target discernment was only less efficient with four display elements. In particular, with four elements in the display, there are only two differently oriented red items, one target, and one distractor.

Consider, for example, a pair of consecutive trials in which the display contains, on the first trial, a horizontal-*red* target, one vertical-*red* distractor, and two horizontal-green distractors; and, on the next trial, a vertical-*red* target, one horizontal-*red* distractor, and two vertical-green distractors. Now assume that, on target-present trials, the facilitatory effect of distractor repetition results from prioritized grouping of red distractors. This assumption receives support from the finding (with larger display sizes) that facilitation was larger when the red distractors' orientation was repeated (i.e., with both repetition of the target's and the red distractors' orientation, i.e., sTsD condition, and repetition of the red distractors' orientation alone, i.e., dTsD condition) compared to when the green distractors' orientation, together with that of the target, was repeated (sTdD condition) (for further support, see Appendix). Then, when there are two differently oriented red elements in the display (one of them being the target), there are two ways of making a 'target-present' decision: the decision may be based either on detecting an orientation difference between the red elements, or on checking which one of the two red elements matches the orientation of the green distractors. Given that search operates via the (prioritized grouping of) red elements, the former possibility may be more likely (i.e., without checking of the green distractors to determine target identity). As a result of this, the red distractor might be erroneously selected as the target on some trials (on others, the target is correctly selected). Then, on the next trial, on which both the (red) target and the (red) distractor orientation are changed (dTdD), there may be a bias towards selecting that red element as the target (in this case, correctly) that shares the same orientation as the mistaken target on the preceding trial (Figure 4). This bias – in effect: a form of target-on-target priming – would reduce the RT disadvantage usually found in the dTdD condition; in other words, it would reduce the amount of facilitation usually observed in the sTsD and dTsD conditions (relative to the dTdD condition).[2] In contrast with the 4-element display size conditions, in the conditions with 8 and 16 elements, there were three and, respectively, seven red distractors, so that the uniquely oriented target was unlikely to be mis-selected as a distractor, producing large RT advantages for sTsD and dTsD conditions relative to the sTdD and dTdD conditions.

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[2] In some sense, this account resembles that put forward by Bravo and Nakayama (1992) for the prolonged 'pop-out' search RTs they observed with 2-element displays, when it is not immediately clear which of the two elements is the target.

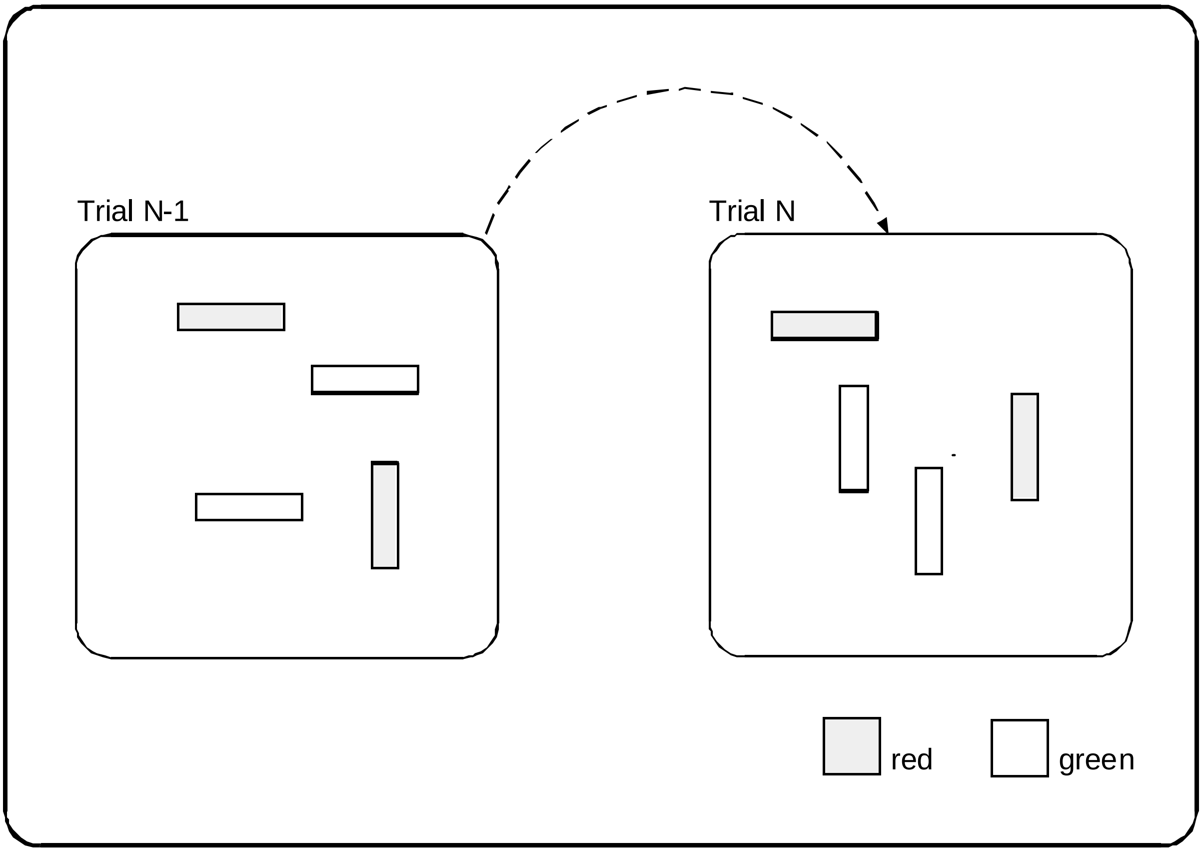

Figure 4: A possible explanation for the lack of facilitatory priming in the 4-element display conditions of Experiment 1A and 1B. In the 4-element conditions, there are 2 red and 2 green elements. One of the red elements is the target and one the distractor. For example, on trial N-1 (left-hand panel of Figure 4), the target is the horizontal bar and the red distractor the vertical bar. Assume that the target-present/-absent decision is based on (subset) search of the red elements (rather than checking which of the two red elements shares its orientation with the green elements). Then, in 50% of the trials, the horizontal bar will be correctly selected as the target and, in the remaining 50%, the vertical bar (i.e., the distractor) will be mistakenly selected. On trial N (right-hand panel of Figure 4), there are again one red-horizontal and one red-vertical bar, but the target is now vertical and the distractor horizontal (dTdD transition). If the vertical red distractor was falsely selected as the target on trial N-1, there may be a tendency to select the same-oriented red bar (which is now the target) on the current trial N. In effect, this (mis-) selection on trial N-1 will 'improve' the baseline RT (dTdD condition). As a result, the RT advantage for the sTsD, sTdD, and dTsD conditions relative to the baseline becomes smaller, making it harder to disentangle target- and distractor-based priming effects.

Some support for the above account (of less efficient target selection amongst 2 red elements with 4-element displays) may also be found in the Kristjánsson et al. study (2002), in which the effects of repeated target and distractor orientation were somewhat smaller with 4-element (8 ms) as compared to 8- and 16-element displays (?12 ms). Nevertheless, two points of difference should be mentioned here: First, the design of the Kristjánsson et al. study did not permit them to distinguish the effects of repeated target and repeated distractor orientation; thus, the larger priming effects with 8- and 16-element displays may be confounded by the repetition of the target orientation, rather than being due to the repetition of the distractor orientation alone. Second, in the present experiments, the priming effects found in the sTdD-, dTsD-, and sTsD-conditions of, on average, 16, 35, and 35 ms, respectively, were much larger relative to those reported by Kristjánsson et al. One possible explanation for the stronger priming effects could be that there were four (present experiment) rather than just two (Kristjánsson et al., 2002) different target and distractor orientation alternatives. This would have increased the uncertainty associated with the possible orientation of the target and distractors on a given trial, which, in turn, could have increased the RT advantage when the red display elements (target, distractors, or both) were the same in orientation on the next trial.

Some support for this suggestion is provided by the analysis of the present data dependent on the number of possible target versus distractor alternatives. While the target- and distractor-based facilitation effects revealed in Experiments 1A and 1B were relatively little affected by the number of target and (red) distractor alternatives, the latter had some discernible effect: The facilitation (37 ms overall) tended to be larger, by 10 ms, when the number of distractor alternatives was 4 rather than just 2 (Experiment 1A vs. Experiment 1B); this effect was evident on both target-absent and -present trials. Thus, the overall dominant distractor priming effect is affected by distractor uncertainty, perhaps because more detailed (i.e., time-consuming) distractor analysis is required in order to discern target presence when the number of distractor alternatives is increased; this would strengthen the ‘set’ for the current type of distractor, leading to stronger priming when this distractor type is repeated (see Müller et al., 2004, for a similar explanation of an increased target-based priming effect under singleton feature search conditions which required detailed analysis of target identity, rather than simply target detection). However, this suggestion is tentative, requiring further investigation.

General Discussion

Several mechanisms have been proposed that could account for efficient visual search for conjunctively defined targets (see Introduction): inhibition of distractor features (Treisman & Sato, 1990), enhancement of target features (Wolfe et al., 1989), feature dissimilarity between target and distractors and similarity amongst distractors (Duncan & Humphreys, 1989), or the priming of target and/or distractor features across consecutive trials (Kristjánsson et al., 2002; Wang, Kristjánsson, & Nakayama, 2001). The present results provide further evidence in favor of the latter account; in addition, they demonstrate that priming derives mainly from the repetition of distractor, rather than that of target, features. [Note, though, that Weidner, Pollmann, Müller, and von Cramon (2002) found large target-based priming effects in a conjunction search task in which the target was defined by a conjunction of a constant, primary dimension, size, and a variable (across trials), secondary dimension, color or motion. In this case, the facilitation deriving from repetition of the secondary target dimension was in excess of 100 ms, which compared with a facilitation effect of approximately 16 ms when the target-defining feature within the secondary dimension was repeated.]

A memory system for priming in visual search

Given that the repetition of display elements’ features across trials can improve search efficiency, how can the memory underlying the feature (repetition) priming be characterized?

One possibility is that it works via an automatic (top-down impenetrable), implicit visual short-term memory (Maljkovic & Nakayama, 1994; Experiment 4). However, recent work by Müller and his colleagues (2003, 2004) suggests that this may not be the whole truth. For example, in a singleton feature search task, Müller et al. (2004) found evidence that (automatic) priming can be influenced by factors associated with the task set. When participants had to explicitly encode (and retain) the target-defining dimension or feature, dimension-specific cross-trial facilitation effects (cf. Müller, Heller, & Ziegler, 1995) were increased relative to a no control condition in which encoding was not required; note, though, that priming (of reduced magnitude) was also manifest in the latter condition. The increased cross-trial facilitation in the ‘encode’ conditions was taken as evidence for top-down modification of a (dimension-specific) visual short-term memory system that, in default mode, operates in a largely automatic fashion.

Perhaps, these discrepant results suggest independent priming mechanisms, one operating at the feature level (e.g., Maljkovic & Nakayama, 1994), which is top-down impenetrable, and one at the dimensional level (e.g., Müller et al., 2003, 2004), which is sensitive to top-down biasing.

Another explanation is suggested by Hillstrom (2000). In her Experiment 1, participants responded to the orientation of a color singleton target that, in one condition, changed its color predictably every two trials. The results were similar to those reported by Maljkovic and Nakayama (1994, Experiment 4), in that a RT advantage was found when the color of the target was repeated on consecutive trials. [However, the search RTs were overall faster, by 115 ms, when the target color changed predictably rather than randomly across trials, a finding interpreted by Hillstrom (2000, p. 803) as an effect of (top-down) “expectancy” – at variance with Maljkovic and Nakayama (1994).] Priming effects were also evident when observers were prevented from operating a simple saliency-based search strategy; for instance, when an additional color singleton (distractor) made it necessary for observers to set themselves, on a trial-by-trial basis, for a particular target feature (Experiment 3), or when they had to set themselves for a particular conjunction of target features (Experiment 4), requiring a template-based search strategy (cf. Duncan & Humphreys, 1989). Hillstrom took the finding of priming effects in a wide variety of search tasks (from singleton feature search to cued feature and conjunction search) to suggest that a single memory mechanism may be responsible for these effects. Interestingly, in the conjunction search task (Experiment 4), repetition did not affect the search time per element (the slope of the search RT/display size function), but rather the base RT (y-intercept of the function). [This was also the case in the present experiments (in which the search times were similar in the sTsD, sTdD, dTsD, and dTdD conditions (15.4, 15.1, 16.5, and 18.4 ms/element, respectively) and in the study of Weidner et al. (2002).] Hillstrom (p. 811) took this to suggest that repetition affects the speed of the spatially parallel enhancement (in Hillstrom's terms, "prioritizing") of target feature coding (cf. Wolfe, 1994).

Based on these findings, Hillstrom (2000) proposed an episodic memory mechanism of "prioritization": If the target features determining selection on a given trial are repeated, a memory trace of the priorities assigned to the display elements on this trial can be carried over to the next trial, expediting the processing of items sharing target features in the new display. In contrast, if the target features change, a new set of priorities must be established, leading to RT costs. [Note that this episodic-memory explanation in some sense resembles the 'weighting' account proposed by Müller and his colleagues (e.g., Müller et al., 1995, 2003). fMRI data suggest that one component of the 'episodic' memory is realized in terms of sustained enhancement of feature coding mechanisms in extrastriate visual areas (e.g., Pollmann, Weidner, Müller, & von Cramon, 2005).]

However, with regard to Hillstrom's (2000) account, the present findings suggest that it is not only, or even foremost, episodic memory for target features which determines the speed of prioritizing the processing of the new display elements; rather, it is episodic memory for distractor features which carries a greater weight.

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Appendix

Further evidence for the proposal that the facilitatory effects in Experiments 1A and 1B resulted from the repetition of the red distractors (i.e., essentially, subset search of the red elements), was provided by a control experiment, henceforth referred to as Experiment 2, which is reported below. In Experiment 2, observers had to search for a uniquely oriented red target. However, in contrast to Experiments 1 and 2, the orientation of the red distractors was (orthogonally) coupled to that of the red target, while the orientation of the green distractors was varied independently of the target orientation. If performance was dependent on (i.e., subset search of) the red display elements, the variation of the green distractors' orientation was not expected to significantly influence the search RTs.

Method

The methodological details were the same as in Experiments 1A and 1B, with the following exceptions:

Ten unpracticed observers (mean age 24.1 years; six females; all reporting normal or corrected-to-normal vision) took part in Experiment 2.

On all trials, the display consisted of a fixed number of eight stimuli (8-element displays in Experiment 1A and 1B). There were 2 target and 2 red distractor alternatives – horizontal and vertical (i.e., if the target was horizontal, the red distractors were vertical; and if the target was vertical, the red distractors were horizontal) and 4 green distractor alternatives – horizontal, vertical, and diagonal (all either left- or right-oblique by 45°, respectively) (i.e., if the target was horizontal, the green distractors were either horizontal, left-, or right oblique; and if the target was vertical, the green distractors were either vertical, left- or right oblique). That is, in contrast to Experiments 1A and 1B, the orientation of the green distractors was varied (repeated) independently of the target orientation (while the red orientation of the red distractors was tied to that of the target). See Figure 5 for all possible target and distractor orientations on a given trial.

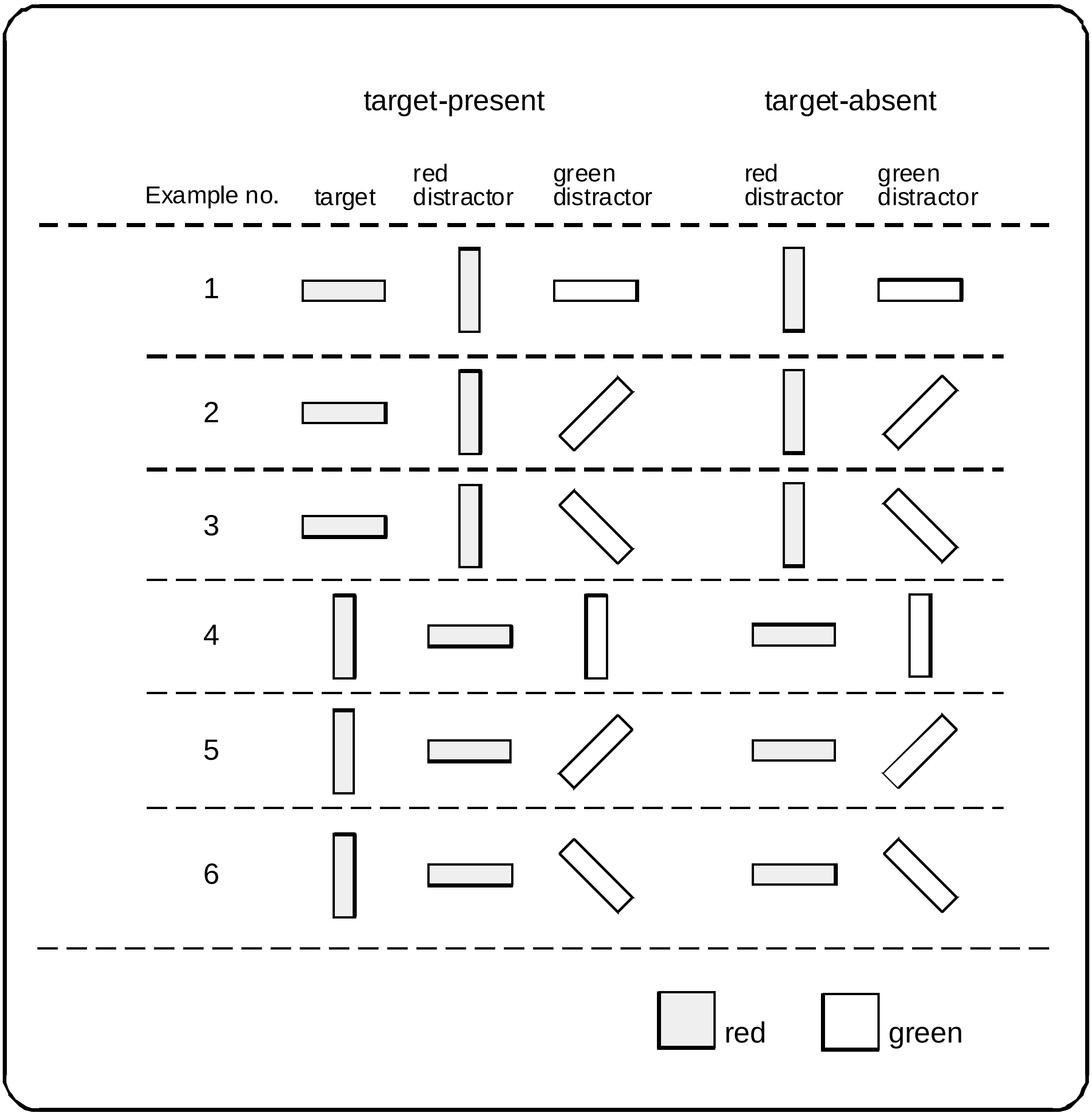

Figure 5: Examples of the search displays used in Experiment 2. If the (red) target was horizontal, it was presented amongst vertical-red and either horizontal- or diagonal-green (all left-oblique or right-oblique by 45°, respectively) distractors. If the target was vertical, it appeared amongst horizontal-red and either vertical- or diagonal-green distractors. In target-absent trials, horizontal-red distractors were presented together with either vertical- or diagonal-green distractors, or vertical-red distractors were displayed together with either horizontal- or diagonal-green distractors.

Experiment 2 consisted of 360 randomly mixed pairs of trials (720 trials in total), representing all 36 different cross-trial contingencies on target-present as well as -absent trials at least five times.

For target-absent trials, the 36 cross-trial contingencies were classified in terms of the sD (same-oriented green distractors; 6/36) and dD conditions (different-oriented green distractors; 30/36); for target-present trials, the 36 cross-trial contingencies were classified in terms of the sTsD (same-oriented target, same-oriented green distractors; 6/36), sTdD (same-oriented target, different-oriented green distractors; 12/36), dTsD (different-oriented target, same-oriented green distractors; 4/36), and dTdD conditions (different-oriented target, different-oriented green distractors; 14/36).

Experiment 2 consisted of eight blocks, each of five (unrecorded) warming-up trials and 90 experimental trials, with blocks separated by short breaks. A session lasts about 40 minutes. At the beginning of Experiment 2, observers performed one block of 77 practice trials (data not recorded).

Results

The correct group mean target-present and -absent RTs were 753 and 776 ms, respectively, overall. The overall error rate was 5.6%, with target misses (4.8%) somewhat less frequent than false alarms (6.7%).

Transitions effects on target-absent RTs. The repetition of same-oriented green distractors expedited responses by 18 ms relative to their non-repetition (738 and 756 ms in the sD and dD conditions, respectively). However, a paired t-test comparing the sD and dD conditions failed to reveal this effect to be statistically reliable [t(1,9)=-1.09; p>.30]. With reference to Experiments 1A and 1B, this indicates that, in Experiment 1, the significant facilitatory effect on target-absent trials resulted from the repetition of same-oriented red (Experiments 1A and 1B), rather than green (Experiment 2), distractors.

Analysis of target-present trials. A separate ANOVA of the target-present RTs with the factor transition (sTsD, sTdD, dTsD, dTdD) revealed its effect to be statistically reliable [F(3,27)=3.68; MS_E=1383; p<.05]. RTs were faster in the sTsD and sTdD conditions (710 and 719 ms, respectively) in comparison with the dTsD and dTdD conditions (750 and 756 ms, respectively). Thus, only the repetition of the red target (and with it the repetition of orthogonally oriented red distractors) produced a facilitatory effect (of approximately 40 ms).

This pattern of effects provides further evidence that, in Experiments 1A and 1B, the facilitatory repetition effect on target-present trials resulted from subset search of the red display elements; that is, observers segmented the visual display on the basis of the (target-defining) color, rather than the orientation, of the search elements.

Chapter 4 - Probing distractor inhibition in visual search: Visual marking

Abstract

Three experiments examined distractor inhibition in parallel (‘pop-out’) visual search. Distractor inhibition was measured in terms of reaction time (RT) to a simple luminance increment probe presented, after the search task response, at display locations that either contained a search distractor (on-probe) or were blank (off-probe). When the search stimuli remained in view, the on-probe (relative to off-probe) RT cost was larger than in a baseline condition in which observers had only to passively view, rather than search, the display. This differential on-probe RT cost, which discounts effects of masking, was interpreted as a measure of distractor inhibition associated with target selection in parallel visual search. Taken together, the results argue that the distractor inhibition is not an artifact of eye movements; it is an object-based and local phenomenon that affects all distractors (of a particular type) in an equal manner - consistent with their parallel inhibitory ‘visual marking’ (c.f. Watson & Humphreys, 1997).

Distractor Inhibition in Visual Search

Posner and Cohen (1984) observed that it takes more time to respond to a target at a recently attended, relative to an unattended, location. They proposed that, shortly after having attended to a location or object, there is a momentary bias against re-attending to it (inhibition of return, IOR) and that this bias modulates spatial selectivity by favoring novel locations in visual scanning (see also Koch & Ullman, 1985, who subsequently incorporated IOR in a computational model of serial search). Klein (1988) tested this proposal by probing for IOR in a serial visual-search task. Observers performed both a parallel- and a serial-search task. On their search task response (target-present or -absent), the search display was replaced by a luminance increment probe to which they had to give a simple reaction time (RT) response. The luminance increment appeared either at a previously empty location (off-probe) or a location that had been occupied by a search display distractor (on-probe). Klein (1988) found that after the performance of a serial relative to a parallel search task, on-probes exhibited an RT-disadvantage (of some of 50 ms on search target-absent trials) relative to off-probes – consistent with the idea that IOR operates in serial visual search. Following Klein's original study, several authors (e.g., Wolfe & Pokorny, 1990), including Klein himself (Klein & Taylor, 1994), were unsuccessful in their attempts to replicate his original findings.

Recently, Müller and von Mühlenen (2000) showed that these on-probe costs in serial (relative to parallel) search were replicable only under two specific conditions: (1) the search display had to remain in view when the luminance increment probe was presented (Experiment 3; see also Takeda & Yagi, 2000), and (2) probes had to appear equally likely at search array and empty locations (Experiment 4). Based on the first of these requirements, they concluded that the IOR effect in serial search is 'object-based' rather than 'space-based' (see also Tipper, Driver, & Weaver, 1991, and Tipper, Weaver, Jerreat, & Burak, 1994, who had demonstrated an 'object-based' component of IOR in variations of Posner and Cohen's, 1984, paradigm). Despite the current controversy concerning the operation of some sort of ‘memory’ in serial visual search (contra memory: e.g., Horowitz & Wolfe, 1998; 2001; 2003; pro memory: e.g., Shore & Klein, 2000; von Mühlenen, Müller, & Müller, 2003), there is evidence for an IOR-like mechanism operating in visual search: This mechanism can be understood as a serial, automatic process of distractor inhibition, which grades distractor ‘objects’ according to some inverse function of (1) the time elapsed since they were last attended (see Danziger, Kingstone, & Snyder, 1998) and (2) how frequently they were attended during some preceding time interval (Posner, Cohen, Choate, Hockey & Maylor, 1984).

While there is evidence of distractor inhibition in serial visual search, distractor inhibition is not usually thought to play a role in parallel search. In fact, this is the very assumption that underlies the logic of Klein’s (1988) paradigm, in which the on-probe (vs. off-probe) disadvantage in serial search is corrected by the on-probe (vs. off-probe) disadvantage in parallel search, which takes into account factors such as forward-masking of the on-probe stimulus by the search array distractor (the assumption being that masking effects are equivalent for both types of search).

More recently, a ‘parallel’ effect of distractor inhibition has been reported by Watson and Humphreys (1997, 1998, 2000; Humphreys, Watson, & Jolicoeur, 2002; Olivers & Humphreys, 2002; for a review see Watson, Humphreys, & Olivers, 2004). They referred to their effect as ‘visual marking’ to distinguish it from ‘inhibition of return’ of attention and characterized it as based on “parallel, top-down attentional processes of inhibition” applied to stimulus locations or stimulus features (Watson & Humphreys, 1997). They used a modified color-shape conjunction search task in which one set of the distractors (the preview-set), all with a common color and shape, was presented before the remaining stimuli which included the target if present (the target-set) Search in this ‘gap’ condition was as efficient as when only the second set of stimuli was presented (single feature condition). The minimum gap time required to separate the two sets of items was about 400 ms, and increasing the gap beyond 400 ms produced few extra gains (with gain measured relative to a standard conjunction or 'no-gap' condition). Watson and Humphreys attributed the gain in the conjunction gap condition to inhibition or 'marking off' of the preview-set distractors. This inhibitory effect was abolished when the preview-set underwent abrupt luminance changes, either decrements or increments, at the same time as the target-set appeared (Experiment 5). Furthermore, the effect was reduced when participants were given a second load task keeping attention at the center of the display while the initial set of distractors was presented (Experiment 8). Note, though, that there is currently a controversy concerning the nature of 'visual marking': is it based on the 'voluntary' inhibition of the pre-view set (the position advocated by Watson and his colleagues) or the 'automatic' facilitation of the new-onset target-set (e.g., Donk & Theeuwes, 2001)? - Whatever the answer, although visual marking might be based on the operation of a 'parallel' (inhibitory or facilitatory) mechanism, it is not thought to play a role in parallel visual search (but rather to facilitate serial search by preferential scanning of 'novel' items).

One account of visual search that postulates a parallel process of distractor inhibition in visual search is the 'Search via Recursive Rejection' (SeRR) model proposed by Humphreys and Müller (1993; Müller, Humphreys, & Donnelly, 1994). According to this model, target-present decisions are reached, as a rule, by the parallel rejection of (groups of) distractors, where the rejection involves a single-step process in parallel search, but a recursive process in serial search. Thus, importantly, on this account, parallel distractor rejection ought to play a role not only in serial visual search, but also in parallel search [1].

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[1] In the SeRR computational model, parallel distractor rejection was designed to implement the mechanism of 'spreading suppression' postulated by Bundesen's (1990, 1998) 'Theory of Visual Attention' and Duncan and Humphreys' (1989) 'Attentional Engagement Theory' of visual search.

The present study, of three experiments, was designed to examine whether (and under what conditions) distractor inhibition occurs in parallel visual search and, if so, to what mechanism (e.g., visual marking) this effect can be attributed to (SeRR as such is neutral with respect to the specific mechanism underlying the distractor ‘rejection’).

Overview of the Experiments

All experiments used a modification of Klein’s (1988) paradigm, following the parallel-search task used by Müller and von Mühlenen (2000). Experiment 1 tested whether distractor inhibition could be observed in a parallel search task (1) when the search display was extinguished after participant’s search-task response, (2) when parts (internal, non-boundary contour) of the search stimuli were extinguished (causing multiple luminance decrements), and when (3) the search display remained in view at the time the luminance increment probe is presented. To rule out possible forward-masking effects of the probe stimulus by the preceding search stimuli, control conditions were run in which observers only had to passively view, rather than actively search, the display. The results showed clear evidence of ‘inhibition’ of search distractor stimuli when the search display remained in view or only the internal parts of the stimuli were removed after the search task response, over and above any forward masking effects. In contrast, there was no evidence for distractor inhibition when the search stimuli were extinguished before the probe stimulus was presented.

Experiment 2 was designed to rule out that the distractor ‘inhibition effects observed in Experiment 1 were caused by eye movements during the search. Experiment 1 had revealed no on-probe costs for targets (only costs for distractors), which could be due to the fact that observers made an eye movement away from central fixation (the position optimal for visual information intake from across the display) to the target. This could, in turn, have diminished the detectability of on-probe stimuli more than that of off-probe stimuli (i.e., irrespective of whether the on-probe stimuli appeared on a target or a distractor) (cf. Zimba & Hughes, 1987). However, Experiment 2 produced evidence for a reduced, but significant distractor inhibition (and target facilitation) even when observers had to fixate the center and eye movements were controlled for.

Experiment 1 had revealed reduced (though significant) distractor inhibition when the internal parts of the search stimuli were extinguished, involving multiple luminance decrements in the display. Experiment 3 was designed to test whether the reduced inhibition was a local effect (confined to the changed stimuli) or a global effect (affecting changed and unchanged stimuli equally). However, the reduced distractor inhibition in the part-off condition of Experiment 1 could also reflect priority of processing new relative to old elements (cf. Yantis & Jonides, 1984). Given that the number of items that can assign attentional priority is limited to four (Yantis & Johnson, 1990), the RT-disadvantage for probes presented on ‘changed’ (i.e., potentially prioritized) search stimuli should be smaller when fewer than four (e.g., two) of the search stimuli items are changed compared to when more (e.g., eight) are changed. Therefore, in Experiment 3 the proportion of changed to unchanged distractors was systematically manipulated. The results revealed reduced inhibition for changed relative to unchanged distractors indicating that luminance decrements reduced the inhibition locally. However, the reduction in inhibition was found to be independent of the number of changed objects. This result was taken as evidence that the reduced RT-disadvantage for changed distractors resulted from a reduce in the inhibition associated with them rather than their prioritized attentional processing.

Overall, the results of Experiments 1–3 suggests that a process of distractor inhibition, which cannot be explained by forward-masking nor eye movements alone, plays a crucial role in parallel visual search. The inhibition operates in object-based, rather than spatial, coordinates; it is associated with observers’ search-task response; and it is a local phenomenon, affecting all distractors of a particular type in an equal and spatially parallel manner. Taken together, these effects are consistent with inhibitory visual marking of distractor stimuli (cf. Watson & Humphreys, 1997).

Experiment 1

Experiment 1 was designed to investigate whether distractor inhibition could be observed in parallel visual search when (1) the search stimuli were extinguished after observers' search-task response ('display-off'), (2) only the internal (non-boundary contour) parts of the search stimuli were removed ('part-off'), or (3) the stimuli remained in view until the response to a luminance increment, presented to probe distractor inhibition in the search array ('display-on'). These conditions are illustrated in Figure 1. The search displays consisted of varying numbers of outline squares, each containing a corner junction segmenting out their upper-right quadrant. The target was defined by a globally different orientation, a 45?-rotation, relative to the distractors. In one condition, parallel search, observers had to discern the presence of this target in the search array (target-present/absent response). Their search task response then triggered the probe detection task, which required a 'go'-response to the onset of a probe stimulus at an (previously) occupied array location (on-probe) or at an empty location (off-probe), and the withholding of a response when no probe stimulus was presented.

This active search task was compared to a passive-viewing 'baseline' condition. Observers were presented with 'search' array for an amount of time comparable to that in the parallel search condition, but they were instructed to simply 'look at the display' without performing any search (or other task related to these stimuli). To reinforce this instruction, all search array stimuli were the same, that is, there was never an odd-one-out 'target' to capture observers' attention. The stimulus array was presented for a variable period of time between 400 and 800 ms (i.e., within the range taken by observers the parallel search condition to respond target-absent), until a detection probe could be presented, either at an (previously) occupied location (on-probe) or an empty location (off-probe). The observers' only task was to respond as quickly as possible to the onset of probe stimulus.

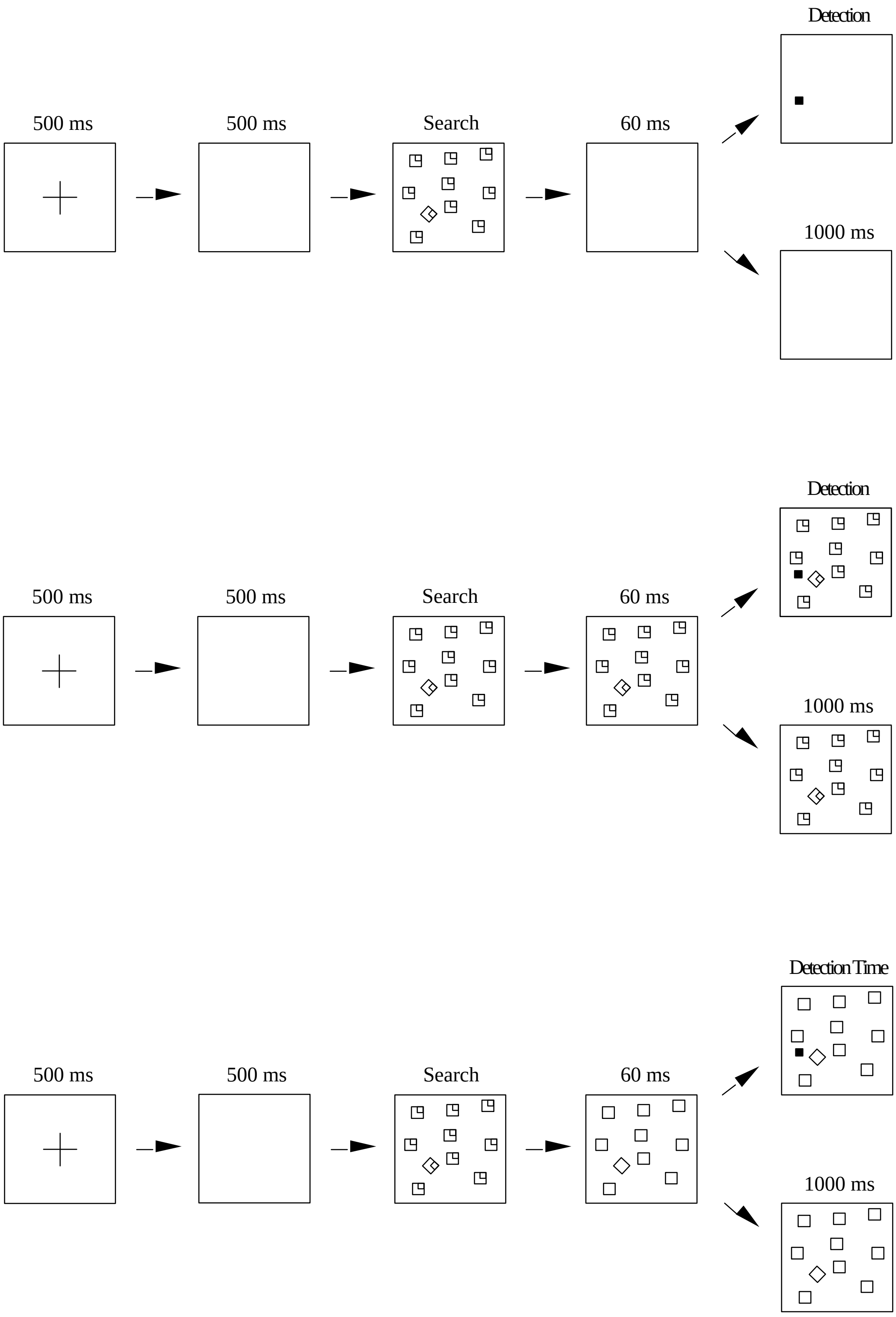

Figure 1. Sequence of frames on a given trial in the display-off (top), display-on (middle), and part-off conditions (bottom) of Experiment 1. The search display depicts a parallel search array consisting of a target and nine distractor stimuli (10-item display; target-present trial). The probe detection display depicts a trial with a luminance increment probe at a previously empty location (off-probe).

The rationale for comparing the parallel-search against the passive-viewing baseline condition followed the technique developed by Klein (1988): Slower RT to on-probes than to off-probes (henceforth referred to as on-probe RT cost) were expected under both parallel-search and passive-viewing conditions, because of visual factors such as masking of on-probe stimuli by the search array stimuli or their sudden offsets (display-off condition). By contrast, such factors should have less (if any) effect on off-probe detection performance. Masking or display-off effects would be equivalent in both parallel-search and passive-viewing conditions. However, if distractor inhibition was operating in parallel visual search, the on-probe RT cost in the search condition would additionally be influenced by inhibition placed on search distractors or their locations. Any such additional component can be estimated by subtracting the on-probe RT in the control condition (in which there can be no distractor inhibition because observers only passively viewed, rather searched, the display) from the cost in the parallel search task. If the residual cost (henceforth referred to as differential on-probe RT cost) in the parallel search condition is positive, it can be interpreted as evidence for distractor inhibition.

Method

Participants. Ten observers (age range 21–40 years; five females; all with normal or corrected-to-normal visual acuity) took part in Experiment 1. They were paid at a rate of Euro 6.50 for a 1-hour session.

Apparatus. The experiment was conducted in a dimly lighted laboratory to minimize reflections on the CRT. Stimuli were presented on a Tektronix 608 CRT with a fast-decay P15 phosphor. The oscilloscope was driven by an Interactive Electronics Systems point plotter (Finley, 1985), controlled by a PC. Observers viewed the monitor from a distance of 57 cm, with head position maintained by the use of a chin rest. Observers search task responses (target-present or -absent) were recorded using the right and left buttons of a serial Microsoft mouse, with track ball removed to improve timing accuracy (Segalowitz & Graves, 1990). Their subsequent probe detection responses were recorded by means of a response key interfaced with the PC via the parallel port.

Stimuli. The stimuli, square ‘boxes’, had a side length of 0.46° (luminance: 0.8 cd/ m^2; monitor background luminance: 0.1 cd/ m^2). Each box contained a small corner junction segmenting out its upper right quadrant. In the parallel-search task, the target was defined by being the only item standing on one corner (i.e., being rotated by 45°), while all distractors stood on one side. In the passive-viewing condition, there was no target item in the display, to reinforce the instruction of passive viewing. The display-size was either two, six or ten (see Figure 1 for an example display; display-size = ten). The search array stimuli occupied randomly chosen locations defined by the intersections of an invisible grid of six x six lines. The grid covered the central 7.82° x 7.82° area of the display (with the total display area being 12.4° x 12.4°). The luminance increment probe stimulus consisted of a bright filled square of side length 0.31° and a luminance of 1.2 cd/m2). This stimulus was presented either at a location (previously) occupied by a search stimulus (on-probe), or on one of the (previously) empty six x six grid locations (off-probe). The likelihood of an on-probe stimulus occurring at the location of the search target was 1/10, to prevent a bias away from the target location. Following the search task response, the search array stimuli could either be (a) extinguished (display-off), (b) partly extinguished (part-off), or (c) remain entirely in view until the end of the trial (display-on).

Design and procedure. Half of the observers started the parallel search condition followed by the passive-viewing condition, and vice versa for the other half. The Experiment had a total of 2,160 trials, 1,440 trials in the search condition, and 720 trials in the passive-viewing condition.

The search condition had 80 trials for each Display-size (two, six, ten) x Target (present, absent) x Display-type (display-on, part-off, display-off) combination. On half of the trials in each Display-size x Target x Display-type condition (720 trials in total), the search task response triggered the presentation of a luminance increment probe. 50% of such stimuli were on-probes (360 trials) and 50% off-probes (360 trials). There were 20 on-probe and 20 off-probe trials for each Display-Size x Target x Display-type combination of the search task. On trials on which no luminance increment stimulus appeared (720 ‘catch’ trials), the search task response initiated the next trial. Within the search condition, all trial types were presented in randomized order.

The passive-viewing condition consisted of 720 trials in total, 80 trials for each Display-size (two, six, ten) x Display-type (display-on, part-off, display-off) condition. On one half of the trials in each condition (360 trials), a probe stimulus was presented; the other half were catch trials (360 trials). Observers were instructed to ‘look at the display and respond to a probe stimulus as quickly as possible’. Note that, on 20% of probe trials, the probe stimulus was presented ‘early’, that is, within 100-300 ms (variable) after the onset of the stimulus array while the stimuli were in view in all conditions. Such early probe trials were included to make observers ‘look at the display’ from the start [2], but the responses on such trials were not analyzed. All trial types were presented in randomized order.

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[2] The presentation of early detection probes on some trials may have made observers ‘search’ for such stimuli in an active manner, rather than viewing the display passively as intended. However, this would be expected to diminish, rather than increase, any differences in on-probe costs RT between the baseline and the parallel search task, providing a conservative test of the hypothesis.

At the start of each trial, a fixation cross was presented for 500 ms in the center of the monitor. After a 'blank' interval of 500 ms, the search array was displayed until the participants responded target-present or -absent, by pressing the right and left buttons, respectively, of the mouse using the middle (present) and index fingers (absent) of the right hand. For the display-off condition, the search task response terminated the search array (top of Figure 1). In the part-off condition (bottom of Figure 1), the internal parts of the search stimuli were removed upon the search task response. In all three display conditions, 60 ms after the search task response, a luminance increment stimulus could be presented. This stimulus was displayed until the observer pressed a single response key with their left-hand index finger. At this point, the detection probe and, in the display-on and part-off conditions, the search array was completely extinguished. On trials on which no detection probe was presented, the search and part-off display or the 'blank' display remained in view for 1.000 ms. When an observer had made an incorrect search task response (target miss or false alarm), he/she was alerted to his/her error by a brief computer-generated 'bleep'. No feedback was provided with respect to the probe detection errors: probe detection responses on catch trials, or anticipation responses on trials on which a probe was presented (RT less than 100 ms). The inter-trial interval was 1,000 ms if no error signal sounded and 2,000 ms after an error signal.

The physical conditions in the passive-viewing condition closely matched those of the search task. After a fixation cross was presented for 500 ms and a 'blank' interval of 500 ms, the search stimuli were presented for a variable time between 400 and 800 ms. Next, the array of stimuli was extinguished (display-off condition); or the internal corner junctions, but not the external contour, of the stimuli were removed (part-off condition); or the stimuli remained in view (display-on condition). At a time lag of 60 ms after this event (or non-event in third condition), a detection probe could be presented, either at an (previously) occupied location (on-probe) or at an empty location (off-probe). On trials on which no detection probe was presented (catch trials), nothing further happened until 1,400 ms after the presentation of the stimulus array (i.e., the display remained completely blank in the display-off condition). In summary, the crucial difference between the search and passive-viewing conditions was one in observers' task set, namely: No search was to be performed prior to the probe detection task.

The experiments were conducted over three days. On day one, observers practiced the parallel search and passive-viewing tasks for about 30 minutes (data not recorded). On day two and three, they performed the two conditions in counterbalanced order. The parallel search task consisted of 18 blocks, divided into two sessions of nine blocks each, with sessions separated by a break of at least 15 minutes, and the passive-viewing task consisted of nine blocks. Each block consisted of five warming-up trials and 80 experimental trials, with blocks separated by short breaks.

Probe RT analysis. Probe-detection RT was analyzed for evidence of distractor inhibition according to the technique developed by Klein (1988; see above). Note that on-probe trials were analyzed only if the detection probe appeared at the location (previously) occupied by a search distractor and not if it appeared at the location of a search target. Furthermore, probe RTs were not analyzed if preceded by an incorrect search task response. In this and all the subsequent experiments, the off-probe RTs and the on-distractor-probe RTs were combined across search target-absent and -present trials because preliminary ANOVA's failed to reveal any differences in off-probe RTs and in on-distractor-probe RTs between target-absent and -present trials.

Results

Search performance. In the search task of Experiment 1, correct target-present RTs were faster than correct target-absent RTs (642 vs. 727 ms). The error rate was 2.0% overall, with fewer false alarms than target misses (1.0 vs. 3.0%).

Probe detection performance. Figure 2 presents the correct group mean probe detection RTs as a function of display-type, separately if displays contained two, six or ten search stimuli (top, middle, and bottom row, respectively) and for on- and off-probes in the parallel search and passive-viewing tasks. In general, off-probes were responded to faster than on-probe stimuli. Furthermore, and most importantly, the RT-disadvantage for on- relative to off-probes was large in the part-off and display-on conditions, and small in the display-off condition.

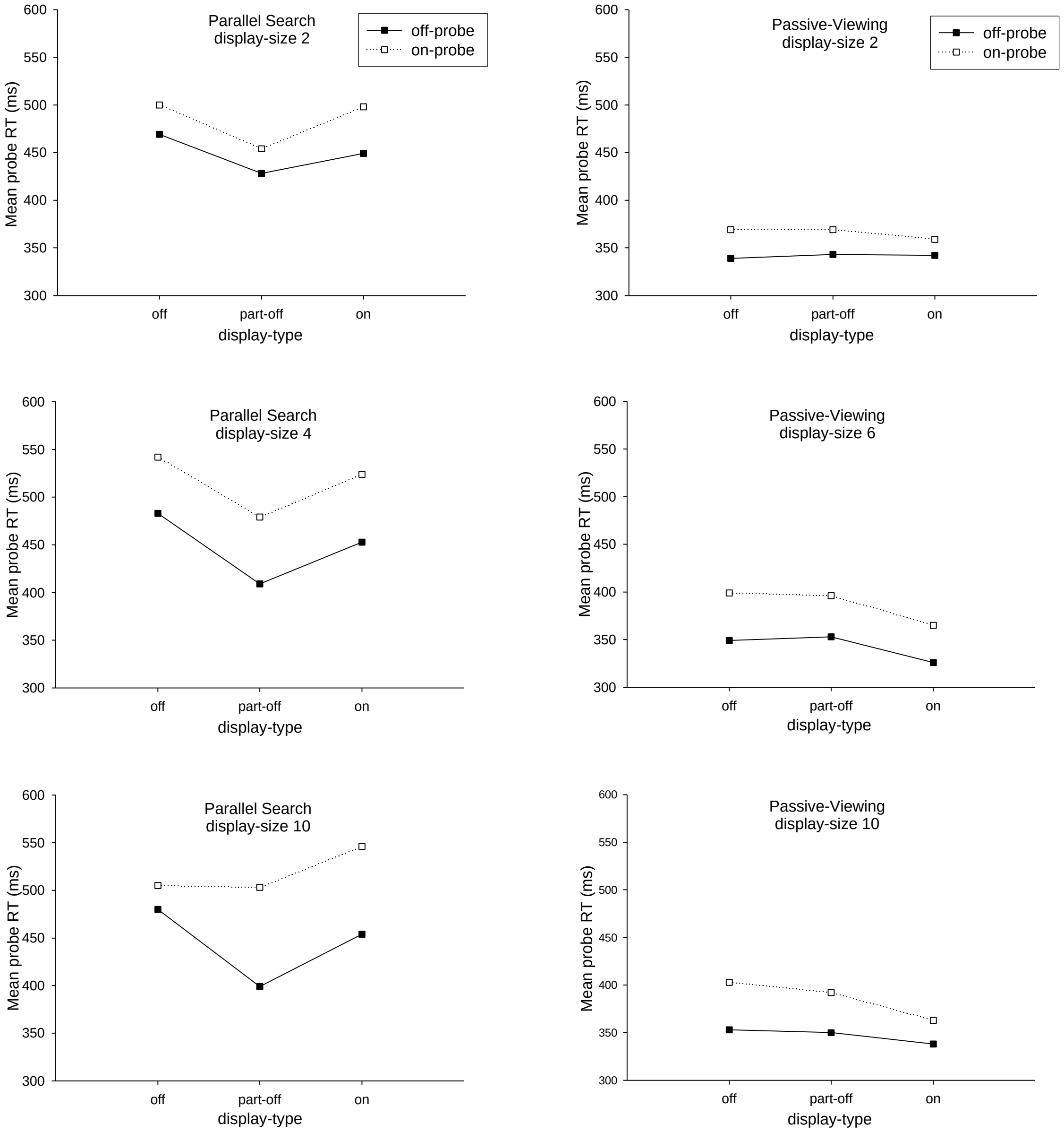

Figure 2. Experiment 1: Group mean on- and off-probe detection times (RT) as a function of display-type, separately to whether displays contained two, six or ten items (top-, middle-, and bottom-panel, respectively) and the parallel search and passive-viewing tasks.

The probe RT-data were examined by an ANOVA with the factors Probe (on-probe, off-probe), Display-size (two, six, ten), Task (parallel search, passive viewing), and Display-type (display-off, part-off, display-on). This ANOVA revealed all main effects (except that of Display-type) and two-way-interactions to be significant, the most interesting effects being the main effect of Probe [F(1,18) = 154.19, p<.00] and the Display-type x Probe interaction [F(2,36) = 5.11, p<.01].

On-probes were responded to slower than off-probes (443 versus 395 ms, main effect of Probe). The most important finding was that the magnitude of the RT-disadvantage for on- relative to off-probe stimuli was dependent on the display-type condition: It was larger when the whole stimulus remained on or when only the boxes remained on than when the stimulus display was turned off prior to probe presentation (49, 52, and 41 ms for the display-on, part-off, and display-off conditions, respectively).

<u>Masking.</u> A separate ANOVA of the passive-viewing condition with the factors Probe (on-probe, off-probe) and Display-type (display-off, part-off, display-on) again revealed the main effect of Probe to be significant [344 vs. 379 ms for off- and on-probes, respectively; F(1,18) = 57.68, p<.00] and the Probe x Display-type interaction to be marginally significant [F(2,36) = 2.06, .10<p<.15]. Concerning this interaction, whereas off-probe RTs were relatively unaffected by display-type (347, 349, and 335 ms for the display-off, part-off, and display-on conditions, respectively), on-probe RTs did exhibit an influence: they were 390 and 386 ms for the display-off and part-off conditions, respectively, as compared to 362 ms for the display-on condition. Simple tests revealed the reduced on-probe RT in the display-on condition, relative to the two other conditions, to be significant. This means that the greater on-probe disadvantage in the part-off and display-off conditions relative to the display on condition was caused by factors relatively closely confined to the location of the on-probe stimulus (i.e., visual masking/interference).

Inhibition. The most important comparison concerns that between the on-probe RT cost in the passive-viewing baseline and the cost observed in the parallel-search condition (see Table 1). This comparison revealed that there was little difference in on-probe RT costs when the stimulus display was turned off before the presentation of the detection probe (if anything, the on-probe RT cost was somewhat greater in the baseline condition). However, the on-probe costs were greater, by some 30 to 40 ms, when the boxes or the whole stimulus display remained on and observers had to search the display for a target before switching over to the probe detection task. This differential effect was statistically reliable: An ANOVA with the factors Probe (on-probe, off-probe), Display-type (display-off, part-off, display-on), and Task (parallel search, passive viewing) revealed the three-way interaction to be significant [$F(2,54) = 10.78$, $p<.00$]. This means that the on-probe RT cost in the display-off condition in the parallel search task is entirely attributable to visual interference. In contrast, in the part-off and display-on conditions of the search task, some other inhibitory component associated with the performance of the task increased the on-probe cost over that expected from visual interference alone.

Discussion

Experiment 1 was carried out to examine whether or not distractor inhibition can be observed in a parallel-visual search task (under display conditions that closely matched those used by Müller & von Mühlenen, 2000). To do so, Experiment 1 introduced a passive-viewing baseline condition that was designed to provide a measure of visual interference between the search array and the detection probe stimuli uncontaminated by any factors associated with the requirement to ‘search’ for a target.

The baseline condition showed that visual interference was least in the display-on condition, intermediate in the part-off condition, and greatest in the display-off condition (Table 1). Furthermore, only on-probe RTs exhibited a significant effect of the display-type condition, but not off-probe RTs, suggesting that the greater interference in the part-off and display-off conditions was due to factors spatially confined to the location of the on-probe stimulus. The likely cause of the interference in the display-on condition is masking by the ‘sustained’ display stimulus on the detection probe presented superimposed on that stimulus. The greater on-probe costs in the part-off and display-off conditions can be attributed to the abrupt offset of a stimulus part (part-off) or the whole stimulus (display-off) interfering with the detection of the abrupt onset of the probe stimulus. This added interference may arise within the ‘transient’ visual system (e.g., Breitmeyer & Ganz, 1976) or it might arise due to the offset ‘cue’ (signaling the imminent presentation of the response-relevant stimulus) and the onset target being similar conceptually (e.g., Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994). The fact that the interference is local (not affecting responses to off-probes distant from display array stimuli) would argue in favor of the ‘transient system’ account.

SEARCH CONDITION	**Parallel search**			**Passive viewing**		
DISPLAY -TYPE	Off	Part-off	On	Off	Part-off	On
PROBE						
Off	477	412	452	347	349	335
On-distractor	516	479	523	390	386	362
On-target	465	429	406			
ON-PROBE RT COST						
Distractor	39	67	71	43	37	27
Target	-12	17	-46			
DISTRACTOR INHIBITION						
Distractor	-4	30	44			
TARGET FACILITATION						
Target	-47	-7	-17			

Table 1. Group mean RT (in ms) to on-distractor-, on-target-, and off-probes, and RT-differences between on- and off-probes (on-probe RT cost: On-Off) for the parallel-search and passive-viewing tasks, separately for the display-type conditions (display-off, part-off, display-on) in Experiment 1. Distractor inhibition and target facilitation are estimated by the differential on-probe RT costs between corresponding parallel-search and passive-viewing conditions (data from Experiment 1 are combined for all display-sizes).

Another important finding emerged when physically identical display conditions were compared between the baseline and the parallel-search task. While the on-probe costs were 30 to 44 ms greater in the part-off and display-on conditions of the search task relative to equivalent display conditions in the baseline, there was no differential on-probe cost for the display-off condition (a negative value of four ms indicates that the on-probe RT cost in the baseline was greater than the on-probe cost in the search condition). This suggests that: (1) there is inhibition of distractor stimuli when the search array is in view at the time the detection probe is presented (superimposed on a distractor); and (2) the inhibition is cancelled by the rapid offset of the search stimuli prior to the presentation of the detection probe (in which case the total on-probe cost can be attributed to visual interference in the transient system).

Two important questions arise from this pattern of results: Why would there be inhibition of the search distractors in Experiment 1, given that a detection probe was equally likely to appear at all (occupied as well as empty) display locations, and at what time does the inhibition arise? Since the inhibition was completely reset when the search display stimuli were extinguished prior to the probe presentation (display-off condition), the inhibition does not originate in the probe detection task. This leaves two possibilities: Either the inhibition arises at the point at which observers switch from the search task to the probe detection task (i.e., the inhibition results from the requirement to switch tasks), or it is associated with participants making a search target-present/absent decision – which involves ‘rejection’ of the search array stimuli, at least of the distractors (e.g., Duncan & Humphreys, 1989; Humphreys & Müller, 1993; Müller et al., 1994). According to the second alternative, inhibition is a spatially parallel process of distractor suppression accompanying the selection of a search task response.

If the latter account is correct, there should be inhibition only of the search distractor stimuli, but not of the target, which may receive facilitation. By contrast, the first account would predict that the target is inhibited as well as the distractors. To decide between these alternatives, the probe RT in the search task of Experiment 1 was analyzed for the display-off, part-off, and display-on conditions according to whether the detection on-probe appeared at the target location (search target-present trials) or at a distractor location (search target-absent trials). The results were consistent with the ‘distractor suppression’ account. See Table 1, which presents the on-probe costs for the search condition, separately for target and distractor on-probes, in comparison with the baseline on-probe RT cost. In both the display-off and the display-on condition of the parallel search task, RTs were faster to target on-probes than to off-probes, that is: targets showed no on-probe RT cost at all (display-off: -12 ms; display-on: -46 ms; the part-off condition showed a small on-probe cost of 17 ms). This means that responding to on-probes at target locations was facilitated relative to the baseline (even for the part-off condition). In summary, all display conditions exhibited facilitation for on-target probes (of some 7 to 47 ms), while only the display-on and part-off conditions, but not the display-off condition, showed inhibition for on-distractor probes. This dissociation indicates that facilitation and inhibition arise from separate causes (considered below).

Experiment 2

However, caution is indicated in interpreting this finding, because the smaller on-probe cost for target relative to distractor locations in the display-on and part-off conditions of Experiment 1 may have been due to observers’ fixating the target at the end of the search tasks. Therefore, Experiment 2 was carried out to replicate this finding while controlling for eye movements.

Part of the ‘distractor inhibition’ in the previous part-off and display-on conditions may be attributable to eye movements to the target or any other search display stimulus. If an eye movement was made to, say, the target, fixation was displaced from the most ‘informative’ location in the display, the center. Making an eye movement away from the center would have increased the average distance of the search stimuli from fixation. This, in turn, may have diminished the detectability of on-probe stimuli, more than that of off-probe stimuli (Zimba & Hughes, 1987), appearing at increasingly distant locations. Thus, eye movements in Experiment 1 may have inflated the on-probe costs observed in the parallel search task for on- and part-off displays, relative to equivalent display conditions for passive viewing, in which there was no need to make eye movements. In fact, given that the display center was the ‘optimal’ location for detecting a probe stimulus, it would have been counterproductive for observers to make eye movements in the passive-viewing condition.

However, it is unlikely that the ‘distractor inhibition’ observed in the previous experiment is entirely attributable to eye movements. This is suggested by the fact that there was inhibition of some 30 to 44 ms (part-off, display-on) in the parallel search target-present and -absent trials, the latter with little need (or incentive) to make any eye movements.

Nevertheless, Experiment 2 was intended to examine whether, and to what extent, inhibition and facilitation would be observed under display conditions similar to those in Experiment 1 when eye movements are eliminated.

Experiment 2 consisted of two blocked conditions: search display-on and search display-off, similar to the search display-on and -off conditions of Experiment 1. Display-size was fixed at six stimuli in order to reduce the total number of trials. Observers were presented with a fixation marker cross in the display center, and told to avoid making eye movements during a trial. Within the parallel-search task, all stimuli were identical, except the target, if present, which was rotated by 45°. The display conditions in the passive-viewing task were identical to those of the parallel-search task with the exception that all stimuli had the same orientation and observers only had to view the display.

Method

Participants. Ten unpracticed observers (4 male) took part in Experiment 2, with ages ranging between 18 to 38 years. They performed the parallel-search and baseline conditions on separate days.

Apparatus and Stimuli. No search array or probe stimuli were presented within the central four locations of the six x six matrix defining display locations (so stimuli were at least 2.45° distant from fixation). This was done to ensure that stimuli appeared in extra-foveal vision even on trials on which slow drifts of fixation in the direction of the search target occurred, which are difficult to suppress (e.g., see Appendix B of Müller & Findlay, 1987). Eye movements were monitored using a Skalar Medical Iris limbus tracker.

Design and Procedure. Both the parallel-search and the passive-viewing task consisted of two blocked conditions: display-on and display-off. The orders of Task (parallel search, passive viewing) and Display-type (display-on, display-off) conditions were counterbalanced across observers. In the parallel-search task, each display-type condition consisted of 8 blocks with 60 trials, leading to 480 trials in total (no-probe trials: 2 search target-absent or -present x 120 trials; probe trials: 2 search target-present or -absent x 2 on- or off-probe x 60 trials). On search target-present trials, 1/6 of on-probes appeared at the target location and 5/6 at one of the distractor locations. When participants had to passively view, rather than actively search the monitor, each display condition consisted of 240 trials (4 blocks with 60 trials), with 120 no-probe and 120 probe trials. In Experiment 2, participants were instructed not to make eye movements between the onset of the fixation cross at the start of a trial and a computer-generated ‘bleep’ at the end. The bleep occurred immediately after the detection response on probe trials or 1,000 ms after the search target (absent/present) response on catch trials. Trials on which an eye movement was detected were rejected on-line and rerun later at a random point in the trial block. The percentage of rejected trials was 2.1% in parallel search and 2.7% in the baseline condition of Experiment 2.

Results

Search performance. The group mean target-present and -absent RTs were 537 and 581 ms, respectively (there was little difference between the display-on and display-off conditions). The overall error rate was 3.4%, with target misses (4.3%) more frequent than false alarms (2.5%).

Probe detection performance. Table 2 presents the on-probe RT costs (on-probe RT minus off-probe RT) for the on-target probe and on-distractor-probe conditions of the parallel-search and passive-viewing tasks. Also listed are the relative RT costs for on-target probes and on-distractor-probes in comparison with the on-probe cost in the baseline condition, and the resulting distractor inhibition (target facilitation).

SEARCH CONDITION	**Parallel search**		**Passive-viewing**	
DISPLAY-TYPE	Off	On	Off	On
PROBE				
Off	386	361	368	337
On-distractor	441	415	416	365
On-target	416	375		
ON-PROBE RT COST				
Distractor	55	54	48	28
Target	30	14		
DISTRACTOR INHIBITION				
Distractor	7	26		
TARGET FACILITATION				
Target	-18	-14		

Table 2. Group mean RT (in ms) to on-distractor-, on-target-, and off-probes, and RT-differences between on- and off-probes (on-probe RT cost: On-Off) for the parallel-search and passive-viewing tasks, separately for the display-on and display-off conditions in Experiment 2. Distractor inhibition and target facilitation are estimated by the differential on-probe RT costs between corresponding parallel search and passive-viewing conditions.

Baseline performance. In the baseline condition, the on-probe cost tended to be larger in the display-off condition than in the display-on condition (48 vs. 28 ms), consistent with the previous baseline condition of Experiment 1 (43 vs. 27 ms). This confirms that the abrupt removal of the display stimuli before probe onset interferes more with on-probe detection than their continuing presence in the probe display.

Inhibition. Furthermore, the on-distractor probe cost in the parallel-search task was nearly equivalent to the baseline cost in the display-off condition (55 as compared to 48 ms), but greater in the display-on condition (54 as compared to 28 ms). In other words, there was 'inhibition' in the display-on condition (over and above any visual interference effects estimated in the baseline display-on condition), but no inhibition in the display-off condition. This pattern agrees with the previous Experiment 1. However, the amount of inhibition in the display-on condition was only 26 ms, as compared to 44 ms in the display-on condition of the previous experiment. Although reduced, an ANOVA comparing the on-probe RT costs between the baseline and search task revealed the distractor inhibition to be reliable: There was a marginally significant Task (parallel search, passive viewing) x Display-type (display-on, display-off) interaction: F(1,18) = 4.65, p<.06; a planned (one-tailed) t-test comparing the on-probe RT cost for the display-on condition in the search and passive-viewing task was significant: t(9) = 2.13, p < .05. [Neither ANOVA main effect was significant, Task: F(1,9) = 2.74, and Display-type, F(1,9) = 2.74, both p's>.10].

Facilitation. While only the display-on condition, but not the display-off condition, showed distractor inhibition, both conditions showed evidence for target facilitation. The target on-probe cost in the parallel search task was reliably smaller than the corresponding baseline cost, in both display conditions. An ANOVA of the on-target probe RT cost revealed the main effect of Task (parallel search, baseline) to be significant [F(1,9) = 8.10, p<.025]. The main effect of Display-type (display-on, display-off) was also significant [F(1,9) = 7.39, p<.025], due to the greater target on-probe cost in the display-off condition. But the Task x Display-type interaction was not significant [F(1,9) = 0.06, p=.81] indicating equal facilitation in the display-on and -off conditions. Similar to the reduction in distractor inhibition when eye movements were controlled, the amount of facilitation was also reduced in comparison with the previous Experiment 1 (16 ms as compared to 32 ms; data combined for the display-on and -off conditions of Experiment 1 and 2, respectively).

Discussion

In summary, only the display-on condition, but not the display-off condition, showed evidence of distractor inhibition (of 26 ms). In contrast, both display-type conditions showed evidence of target facilitation (of, in average, 16 ms). The inhibition and facilitation in Experiment 2 was only about half of the magnitude of that in Experiment 1, suggesting that the effects observed previously were inflated by eye movements (e.g., to the target location). However, the fact that the effects remained significant and exhibited the same pattern in Experiment 2 as in the previous experiment argues that facilitation and, in particular, inhibition are not simply an eye movement artifact. Probably, the facilitation is caused by the search target location being covertly attended at the time the probe is presented, regardless of whether or not the target remained visible. However, inhibition is only observed when the distractors remain visible, not when they are removed. This argues against inhibition being coded in spatial coordinates.

Experiment 3

In the display-off condition of Experiment 1, abrupt luminance decrements at distractor locations reduced the inhibition almost instantly (i.e., within 60 ms, the time between the decrement and the onset of the probe stimulus). Furthermore, the degree to which inhibition was reduced depended on the amount of luminance change at an inhibited location: It was less when only a stimulus part was removed (part-off condition) than when the whole stimulus was extinguished (display-off condition), in which case the inhibition was completely reset. Experiment 1 revealed this differential effect to be statistically reliable.

This finding qualifies Yantis and Hillstrom’s (1994) proposal that changes in ‘old’ objects do not capture attention. Yantis and Hillstrom may be right in arguing that the removal of a part of an old stimulus may itself not attract attention. However, it may reset the status of that stimulus, by reducing its inhibition, so that a subsequent salient change at its location can more readily capture attention. This account presupposes that the abrupt removal of parts of distractor stimuli reduces the inhibition locally, only for distractors that were subject to a change, rather than globally, for all distractors irrespective of whether or not they underwent a change (i.e., the removal of parts of some stimuli generates a global signal resetting the status of all inhibited stimuli). In contrast, given Yantis and Johnson's (1990) demonstration that visual attention has approximately a limited number four 'priority tags' available to be allocated to salient luminance changes, the reduced on-probe RT costs in the part-off relative to the display-on condition of Experiment 1 may also reflect priority of processing assigned to them, rather than reduced (local) distractor inhibition.

In particular, Yantis and Johnson (1990) assumed that the visual-attention system can prioritize processing for up to four items marked by (simultaneous) abrupt visual onsets and that priority tags are allocated in parallel to abrupt-onset items and tagged items will be processed prior to untagged items (with untagged abrupt-onset items having the same, lower, priority as no-onset items). The evidence for this account came from a serial visual-search study in which the ratio of abrupt onset to no-onset items was systematically varied. It was found that (1) the search RTs were, on average, faster for abrupt-onset items than for no-onset items; (2) for onset targets, the function relating search RT to the number of abrupt-onset items at first exhibited a shallow increase up to 4 items, while the function for no-onset items showed a steep increase; (3) thereafter, the two functions exhibited equivalent increases. This pattern is as predicted if the attention system has a limited number of four priority tags available.

When considering the part-off condition of Experiment 1, the display-size manipulation revealed differential on-probe RT costs: the on-probe RT costs were 0, 27, and 67 ms for displays of two, six, or ten search stimuli, respectively. With other words, the greater the number of part-offsets, the greater the inhibition associated with search distractors indicating the reduced inhibition to be due to the assignment of a limited number of (four) attentional priority tags (if there are more than four changed items, tags are assigned on a competitive basis yielding, in average, to greater inhibition). However, since in the part-off condition of Experiment 1 all stimulus changes were global, i.e., occurring at all stimulus locations at the same time, Experiment 1 could not distinguish whether the abrupt luminance decrements (part-offsets) reduced the inhibition locally or globally and hence, it could not differentiate between the attentional priority and the reduced inhibition account.

Therefore, Experiment 3 was carried out which used a logic adopted from Yantis and Johnson (1990): systematic variation of the ratio of changed (part-off) to unchanged distractors, in order to examine whether the reduced on-probe RT cost for changed distractors in the present paradigm reflect priority assigned to them, rather than reduced distractor inhibition.

Method

Participants. Eight new and unpracticed observers (four men; ages ranging from 21–28 years; all reported normal or corrected-to-normal vision) took part in Experiment 3.

Stimuli. The displays consisted of a fixed number of ten search array stimuli, which could be followed by a (luminance increment) detection probe superimposed on the search stimuli. After the search task response (present/absent) or 400–800 ms following display onset in the passive viewing-condition, the internal corner junctions of either two, four or eight distractors were extinguished. Thus, the stimulus conditions in Experiment 3 matched those of the part-off condition in Experiment 1, except that the disappearance of the internal L-junctions was varied systematically.

Design and Procedure. The search condition consisted of 960 experimental trials (Target: present or absent x Distractor-change: two, four, or eight x 160 trials). On half the trials (480 trials in total), the search task response triggered the presentation of a luminance increment probe. 50% of these stimuli were off-probes and 50% on-probes (240 trials each). Of the on-probes, 50% were presented on changed and 50% on unchanged distractors (120 trials each). There were 20 probes on-changed distractors, 20 on-unchanged distractors, and

40 off-probes for each Target x Distractor-change condition. The passive-viewing condition consisted of 480 trials (Distractor-change: two, four, or eight x 160 trials). On half the trials (240 trials), a probe stimulus was presented either on a changed or an unchanged distractor, or at an empty location, analogously to the search task. In both tasks, all trial types were presented in randomized order. Overall, the parallel search task consisted of 16 blocks and the passive-viewing task of eight blocks, with five warming-up trials plus 60 experimental trials.

The experiment was conducted over three days. On day one, observers practiced the two tasks (for 30 minutes), and on days two and three they performed the parallel search and passive-viewing conditions, with order counterbalanced across observers.

Results

Search performance. Target-present RTs were faster than target-absent RTs (613 vs. 633 ms), and target misses were somewhat less frequent than false alarms (3.4% vs. 4.6%, respectively).

Probe detection performance. Figure 4 presents the group mean simple RTs to on-probe and off-probe stimuli as a function of Display-change, separately for probes on-changed distractors, on-unchanged distractors, and off-probes, dependent on whether observers actively searched (left-hand panel) or passively viewed (right-hand panel) the display.

Inhibition. An ANOVA of the on-probe RT cost, with the factors Distractor (changed, unchanged) and Task (parallel search, passive viewing) revealed significant main effects of Distractor [F(1,7) = 9.14, p<.05)] and Task [F(1,7) = 9.22, p<.05]; the Task x Distractor interaction did not reach the level of significance [F(1,7) = 2.85, .15>p>.05]. The main effect of distractor occurred because the on-probe RT costs were reduced for changed relative to unchanged distractors (61 ms as compared to 85 ms). The main effect of task occurred because the on-probe RT costs were reduced, overall, in the passive viewing relative to the search task (54 ms as compared to 92 ms).

It is important to note that the effect of distractor change was mainly due to the on-probe RT costs in the parallel-search task (75 and 110 ms for changed and unchanged distractors, respectively), whereas the on-probe RT cost in the baseline condition was little affected by the distractor change (47 and 60 ms for changed and not-changed distractors, respectively). Simple tests of the on-probe RT costs, which were conducted because the Task (parallel search, passive viewing) x Distractor (changed, unchanged) interaction failed significance in the above ANOVA, revealed the distractor change effect to be significant for the search task [t(7)=3.186, p<.05], but not the passive viewing task [t(7) = 1.37, p>.20]. This provides evidence that luminance decrements reduce the inhibition associated with search distractors locally, that is, only for stimuli that were subject to a change, or, alternatively, that they simply facilitated the response to stimuli that were subject to such changes (attentional priority; Yantis & Johnson, 1990; Donk & Theeuwes, 2001).

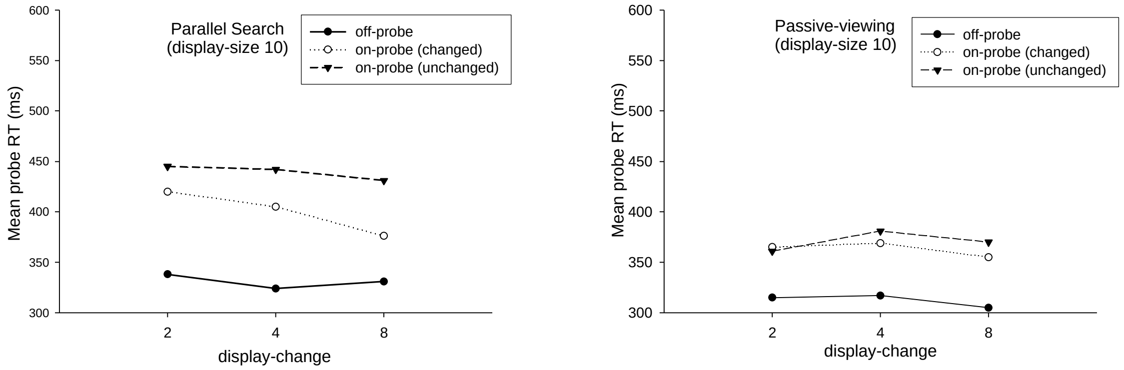

Figure 3. Experiment 3: Group mean probe detection times (RT) for the parallel search and passive-viewing tasks (left- and right-hand panel, respectively), as a function of the number (two, four, or eight = Display-Change) of changed ('part-off') distractors, separately for probes on-changed and on-no changed distractors and for off-probes at blank locations.

Differential inhibition. If the reduced on-probe RT cost for changed distractor stimuli reflects priority of processing assigned to them (c.f. Yantis & Johnson, 1990), then the inhibition for changed distractors should be smaller when there are two (i.e., < 4) changed items than when there are eight (i.e., > 4). To examine this, a second ANOVA of differential 'distractor inhibition' (i.e., the difference between corresponding on-probe RT costs in the parallel-search and passive-viewing tasks, separated for the number of changed distractors), with the factors Distractor-change (changed, unchanged) and Display-change (two, four, and eight changed distractors), was carried out. The most important (non-) finding was that the Distractor-change x Display-change interaction was far from significance [F(2,14) = 0.14, p>.80]. Further, there was no main effect of Display-change [F(2,14) = 0.89, p>.40], but a significant effect of Distractor-change [28 ms for changed as compared to 50 ms for unchanged distractors; [F(1,7) = 8.54, p<.05; main effect of Distractor-change]. Thus, distractor inhibition was independent of the number of changed distractors (in particular, distractor inhibition was not reduced with two as compared to eight changed distractors in the display). This argues against an explanation of the reduced RT-disadvantages for changed relative to unchanged distractors in terms of the attentional priority account.

SEARCH CONDITION	**Parallel search**			**Passive-viewing**		
DISPLAY-CHANGE	2	4	8	2	4	8
PROBE						
Off	343	332	339	321	323	311
On-changed distractors	430	407	401	367	371	358
On-unchanged distractors	454	442	449	371	389	375
ON-PROBE RT COST						
Changed distractors	87	75	62	46	48	47
Unchanged distractors	111	110	110	50	66	64
DISTRACTOR INHIBITION						
Changed distractors	41	28	15			
Unchanged distractors	61	43	46			

Table 3. Group mean RT (in ms) to off-probes and to probes on-changed and on-unchanged distractors as a function of Display-change, i.e., the number of changed distractors (two, four, eight) and corresponding RT-differences between on- and off-probes (on-probe RT cost: On-Off) for the parallel search and passive-viewing tasks in Experiment 3. Distractor inhibition is estimated by the differential on-probe RT cost between corresponding search and passive viewing conditions.

Discussion

Experiment 3 was designed to measure RT-costs for on- relative to off-probes under conditions in which the internal parts of either two, four or eight distractor stimuli were removed. This was intended to account the reduced on-probe RT costs in the part-off condition of Experiment 1. On the basis of Experiment 1, it was not possible to decide whether the reduced RT-disadvantage in the part-off condition reflected the assignment of attentional priority rather than a reduction in distractor inhibition for the part-offset stimuli.

Experiment 3 revealed reduced on-probe RT costs for changed as compared to unchanged distractors (relative to the passive-viewing baseline), replicating the major finding of Experiment 1. However, the data of Experiment 3 rule out this reduced on-probe RT cost to be due to priority of processing assigned to the changed stimuli (c.f. Yantis & Johnson, 1990): at variance with the prediction from the attentional-priority account, there was no indication of differential magnitudes of distractor inhibition when either two (i.e., < 4), 4, or eight (i.e., > 4) search distractors were changed.

Thus, because the luminance decrement ‘signal’ reduces inhibition only for changed stimuli, distractor inhibition can be characterized as a local phenomenon, affecting all search stimuli of a particular type in an equal and spatially parallel manner. Consequently, the distractor inhibition in parallel visual search, demonstrated here using a probe detection technique, can be considered as an instance of inhibitory ‘visual marking’ (considered below).

General Discussion

Distractor Inhibition in Parallel Visual Search

The present experiments produced evidence for distractor inhibition operating in parallel visual search. The baseline condition of Experiment 1 required observers only to note the presence of stimuli without actively searching through them when, similar to the parallel-search task, the search display stimuli were completely removed (display-off), remained in view (display-on), or the internal L-junctions of the search stimuli were extinguished (part-off) prior to probe presentation. The results were: (1) no differential on-probe RT cost between the two task conditions when the display stimuli were turned off before the presentation of the detection probe; but (2) an increased on-probe RT cost of up to 30 to 40 ms in the parallel-search task (over and above any cost attributable to visual interference) when the detection probe was presented superimposed on a distractor stimulus that remained on (wholly or in part) after the search-task response. The second point can be taken as evidence for distractor inhibition in parallel visual search.

Furthermore, the pattern of effects revealed in Experiment 1 throws light on the time at which the distractor inhibition arises and the function that it serves in visual search. There was no evidence of any inhibition when the display stimuli were not to be searched, so the inhibition does not originate in the probe detection task. In addition, inhibition affected RTs only to on-distractor probes, but not to on-target probes (which showed facilitation). This suggests that inhibition is associated with the search target-present/absent decision – which involves ‘rejection’ of the search array distractors (e.g., Duncan & Humphreys, 1989; Humphreys & Müller, 1993; Müller et al., 1994). Furthermore, distractor inhibition was dependent on the distractors remaining in view, in contrast to target facilitation (which was evident irrespective of whether or not the target remained visible).

Distractor inhibition was still evident in Experiment 2, in which observers were prevented from making eye movements (through the distractor inhibition was halved in magnitude in the search condition of Experiment 2). Likewise, the effect of target facilitation was replicated in Experiment 2, but it was also reduced in magnitude when eye movements were eliminated.

Since there was a reduction in distractor inhibition in Experiment 1 for the part-off relative to the display-on condition, in Experiment 3, the number of changed distractors was systematically varied (while keeping the total number of stimuli constant): two, four, or eight. This variation had no differential impact on distractor inhibition (a differential impact would have been consistent with attentional prioritization of changed distractors), consistent with the (distractor) changes reducing the distractor inhibition locally.

Several conclusions can be drawn from this pattern of effects:

(1) There is inhibition of search distractors when the stimuli are visible at the time the detection probe is presented superimposed on a distractor.

(2) The inhibition affects all distractors of a particular type equally and simultaneously. It is found at randomly selected distractor locations, regardless of whether a target was present or absent.

(3) The inhibition is attentional, top-down, in nature. It depends on the relevance of the display stimuli for the participant's task: there is no inhibition when the stimuli are not to be searched.

(4) The inhibition is canceled by the abrupt offset of the search stimuli prior to the presentation of the detection probe, in which case the total on-probe RT cost can be attributed to visual interference in the transient visual system.

(5) The inhibition is reduced by part-offsets (changes) of display elements. This reduction in inhibition is local, that is, it affects all changed distractors in an equal and spatially parallel manner.

(6) The distractor inhibition is object-based, observed only when the search stimuli are in view at the onset of the detection probe. The target facilitation, by contrast, is location-based, observed regardless of whether the target remains in view or not.

(7) Distractor inhibition operates from some form of short-term 'object' memory representation, which is removed when the distractors are extinguished.

The search distractor inhibition demonstrated in the present experiments is remarkably similar to the 'visual marking' effect described by Watson and Humphreys (1997). The similarity also applies to the time course of visual marking, which, according to Watson and Humphreys, takes at least 400 ms to become fully effectual. Judging from the y-intercepts of the search RT functions in the present experiments, the participants had a similar length of time after initiating the search task response to inhibit the search distractors (the presentation of the detection probe was triggered by the overt search task response). One further similarity concerns Watson and Humphreys' report (1997) that visual marking was abolished in their conjunction 'gap' paradigm when abrupt luminance changes, increments or decrements, occurred at the initial distractor locations at the same time as the new stimuli. In the present experiments, abrupt luminance decrements at inhibited locations reduced the inhibition almost instantly (i.e., within 60 ms, the time between the decrement and the onset of the probe stimulus), but in addition, the degree to which inhibition was reduced depended on the amount of luminance change at an inhibited location: It was less when only a stimulus part was removed than when the whole stimulus was extinguished, in which case the inhibition was completely reset. Moreover, the inhibition was also equally reduced when a variable number (of two, four, or eight) of the search stimuli were changed by a luminance decrement, indicating that part-offsets of search stimuli reduce the inhibition associated with them locally.

If part-offsets reduce inhibition at more than four locations, then there must be inhibition at more than four locations; that is, the capacity of the inhibitory effect exceeds the capacity of visual short-term memory (VSTM) of approximately four to six elements/locations (e. g. Phillips, 1974). Our experiments have not revealed a capacity-limit: In Experiment 3, ten items (or more) may be inhibited! Support for a larger capacity of VSTM was found in the study of Jiang and Wang (2004). In their Experiment 3, participants' task was to report the orientation of the target letter T (either left, right, up, or down), which was presented amongst T and L distractors. One half of the distractors (the preview-set, consisting of 'old T's) was presented before the other half (the target-set, consisting of 'new L's' including the target letter T). There were four main display conditions: In the easy-6 and easy-12 conditions, the target-set consisted of six or twelve new display items, respectively, and in both conditions the target could be easily detected, because its shape was dissimilar to the new L distractors (the offset in the intersection of the L distractors was relatively large). In the <u>feature-6</u> and <u>feature-12</u> conditions, the target-set consisted of six or twelve new items, respectively, and in both conditions the target could again be easily detected, because its color was now different from the new L distractors. It was found that the difference between the feature-6 and feature-12 conditions (as indexed by participants' accuracy) was much smaller than the difference between the easy-6 and easy-12 conditions. Because in the two feature conditions search performance was (relatively) unaffected by the display-size manipulation, the authors concluded that the memory underlying these two conditions was different from VSTM (with reference to its spatial attributes). Further, since memory performance decayed rapidly (as indicated by the comparison between the easy-6 and easy-12 conditions) this again was taken as evidence for a memory different from VSTM (with reference to its temporal characteristics). Therefore, Jiang and Wang proposed an 'asynchrony-memory', which should in its formation be associated with the onset of the new display items. Further, its capacity was assumed to be large in the spatial but limited in the temporal region.

However, since in our experiments there was no temporal segregation between old and new display items, the notion of an 'asynchrony memory' is inappropriate to explain the present findings. Rather than a fast decaying but spatially unlimited memory for 'part-offset' elements, the changed search distractors may be grouped on the basis of their local spatial relationships (Watson, 2001) to form a single virtual object (Yantis, 1992) associated with a memory template, which in turn leads to an improvement (in this case the reduction) of the inhibitory process (considered below).

Watson and Humphreys (1997) conceive of their visual marking effect in terms of "a mechanism for optimizing selection of new objects by de-prioritizing selection of old objects", which operates through inhibition "applied either to the locations of static stimuli or to object properties when stimuli are moving (e.g., inhibit all green stimuli)". Note, however, that their gap paradigm allowed Watson and Humphreys only to infer inhibition of the initial set of stimuli from the increase in search efficiency for the second set. Their paradigm was designed to show that search of the second set of stimuli was unaffected by the first set, which is not necessarily equivalent to the first set being inhibited below baseline level. The findings of Watson and Humphreys could also be explained if the attentional priority of the stimuli in the first set was simply nulled.

To test between these alternatives, Watson and Humphreys (2000) used a probe-dot paradigm and provided evidence that support the inhibitory process. As in their classical study (Watson & Humphreys, 1997), participants searched for a conjunction target, a blue H amongst blue A’s and green H’s. There were two major conditions: Firstly, a standard conjunction search in which participants made a present/absent judgment for the blue H target. The second was a gap condition in which the presentation of the preview-set (the ‘old’green H’s) was temporally segregated from the presentation of the target-set (the ‘new’ blue A’s including the green H target). In their Experiment 1, a tone indicated to participants to detect the presence or absence of the probe-dot within the distractors. In the gap-condition it was found that participants were significantly less able to detect probe-dots appearing within the old green H’s than the new blue H items. Further, this performance decrement for probes appearing within the green H’s was not evident in the standard conjunction search condition indicating that inhibition is applied to the old distractors in the gap-condition.

However, Donk and Theeuwes (2001) have generally questioned this explanation of the marking-effect. In a series of experiments they investigated the processing of abrupt onset items (e. g., Yantis & Jonides, 1984; Martin-Emerson & Kramer, 1997) by manipulating the ‘degree of onset’. The participants performed a difficult letter search task (cf. Theeuwes et al., 1998), with the display items being equiluminant to the background. In Experiment 1, both the old and new items were equiluminant to the background. The results showed that search performance varied with the number of old and new items, which is inconsistent with the inhibitory account (if the inhibition of old search items was due to the marking-effect, then only the number of new elements should have affected search performance). In Experiment 3, only the old distractors were equiluminant to the background. Under this condition, search performance revealed to be affected only by the number of new display items. From that finding Donk and Theeuwes concluded that the visual marking effect required that the new items onset with a luminance increment, i.e., that it is the prioritization of the new rather than the inhibition of the old items that accounts for the visual marking effect. However, caution is indicated in interpreting these findings. The design of the experiments differed from that of Watson and Humphreys (1997) in that rather than comparing the gap-condition with a conjunction or feature search condition, the number of old versus new items was systematically varied. Further the results of the experiments reported in this article can be seen as in conflict with Donk and Theeuwes' assumption. Although the probe detection technique used here provided evidence for the attentional prioritization of changed display elements, this prioritization was due to a reduction in the inhibition associated with them (in other words, the priority of processing changed elements resulted from the inhibition of other elements and not from the fact that they appeared as changed display objects alone).

Mechanisms of distractor inhibition in visual search

Given that distractor suppression is associated with response selection, then how might it work? One possibility is that it operates via some form of 'memory template' (cf. Duncan & Humphreys, 1989; Humphreys & Müller, 1993; Müller et al., 1994) coding distractor attributes. For example, in Humphreys and Müller's SeRR model of visual search, target and distractor templates compete to determine the search response. The templates are connected to all feature analyzer units coding the target and the distractors (target and distractor templates may receive activation from the same type of analyzers if the target and distractor are featurally similar), and to location units which code the spatial coordinates of the search stimuli and gate the activity of feature analyzers through to the template units [3]. As soon as, say, the target template wins the competition (i.e., as soon as a target-present response is selected), all active distractor templates are inhibited, which in turn suppresses all location units except for those supported by activation from target feature analyzers. In this way, distractor inhibition does not affect feature coding as such, but rather the gating of distractor feature information onto the template units 4. This means that distractor inhibition is object-based in the sense that it operates from short-term memory templates for objects, but space-based in the sense that it acts on location units gating distractor feature information through to the template units. Note that, in SeRR, the inhibition of distractor templates is not equivalent to their removal; the removal of inhibited templates would release the inhibition of distractor locations. One perhaps questionable assumption made by SeRR is the idea of a general map of locations. However, one could easily imagine some alternative scheme in which template-based inhibition would act directly on location (saliency) maps specific to feature dimensions (cf. Phaf, Van der Heijden, & Hudson, 1990; see also Duncan, Humphreys, & Ward, 1997).

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[3] In this respect, the map of locations serves an analogous function to the overall ‘saliency’ map in Koch and Ullman’s (1985) model and Wolfe’s (1994; Cave & Wolfe, 1990) Guided Search model.

[4] What is inhibited, according to Watson and Humphreys (1997), are the locations of static stimuli, but the features (e.g., color) of moving stimuli. The present experiments, which used only static stimuli, do not bear on this issue.

There is physiological evidence of distractor elimination in response selection from neurons in the anterior inferior temporal (IT) cortex of the monkey (Chelazzi, Miller, Duncan, & Desimone, 1993). Chelazzi et al. showed that IT neurons responding to pre-cued target (form) attributes could be pre-activated and sustained their firing throughout the subsequent search of the display array, providing some form of memory template for the target. Other IT neurons responding to non-target attributes were also activated during the search, suggesting that multiple template representations may be co-active. 90 to 120 ms before response (an eye movement to the target), IT neurons corresponding to non-target objects were suppressed, as if "the target stimulus 'captured' the response of the cell, so that neuronal activity would reflect only the target's properties" (p. 344) [5].

Further evidence of top-down modulation of processing within the pathways linked to the inferior temporal lobe comes from work by Motter (1994a, b). He demonstrated that activity in cells in area V4 of the rhesus monkey could be modulated by the specification (cueing) of the color defining the target object (a colored bar whose orientation had to be reported). V4 cells that had objects of the target color in their receptive fields (RFs) became more excited and cells with objects of other colors in their RFs became suppressed. This modulation of V4 cells occurred in parallel across the visual field; it did not require the target color to be continuously displayed, i.e., it occurred even when the monkey had just a memory of the target color; but modulation was not observed under passive viewing conditions.

Motter (1994b) considered the possibility that the goal-dependent modulation of V4 cells originates in IT cortex and involves "a feedback control system" [6]: "Neurons in several [especially more anterior] areas in inferior temporal cortex [selective for particular sets of stimulus features] have been shown to maintain their discharge activity during delay periods in visual memory tasks ... The presence of clear anatomical connections between V4 and interior temporal cortex suggests one avenue by which mnemonic representations of the cue information can gain access to V4" (p. 2197).

One further interesting aspect of the behavior of “many of the V4 neurons studied” by Motter (1994b) was that they “responded to a reasonably wide band of colors ... even the two best ‘colors’ could be paired, and differential driving [modulation] could be obtained. This differential activation implies that the control system is able to shut down effectively the synaptic impact of all but one of many color inputs. ... [This] suggests that what is being selected may not be a particular color but instead a particular relationship of the selected color to other color features in general” (p. 2197). Restated, differential activation is exhibited by cells coding target something like color ‘saliency’, rather than the target color feature as such. This would be consistent with the idea of template-based inhibition acting directly on saliency (location) maps specific to feature dimensions.

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[5] The behavior of the IT cells recorded by Chelazzi et al. (1993) is relatively independent of the particular response required (IT cells have large receptive fields, though they retain some spatial, retinotopic, information). “... a later study using target selection by manual lever release [rather than a saccadic response] gave very similar results” (John Duncan, personal communication, 26 October 1995). In other words, IT neurons may serve as ‘general’ memory templates involved in singling out targets for all types of response.

[6] There is neurophysiological evidence (cf. Spratling & Johnson, 2004; see Treue, 2003 for a review) that neuronal feedback systems, originating in higher cortical areas, are involved in the control of e.g., eye movements and spatial attention.

Conclusion

Recently, several mechanisms that can regulate attentional prioritization have been proposed: The FINST mechanism for simultaneously tagging or indexing a limited number of proto-objects (estimated at about four to five) to which attention can be deployed rapidly and efficiently (e.g. Pylyshyn, 1989; Pylyshyn, 2001; Pylyshyn & Storm, 1988; Pylyshyn, Burkell, Fisher, Sears, Schmidt & Trick, 1994; Burkell & Pylyshyn, 1997; Scholl, Pylyshyn & Feldman, 2001); the deployment of attention to objects on the basis of an ‘overall’ saliency map for the various feature dimensions (typically co-operating with mechanisms for top-down influences on selection such as pre-activation of maps of unit coding target features) (e.g., Cave & Wolfe, 1990; Koch & Ullman, 1985; Müller, Heller, & Ziegler, 1995; Nothdurft, 1992, 1993; Treisman & Sato, 1990; Wolfe, 1994); the predisposition of the visual system to attend to objects that require the creation of a new perceptual object representation (e.g., Jonides, 1981; Theeuwes, 1991; Donk & Theeuwes, 2001; Hillstrom & Yantis, 1994; Yantis & Johnson, 1990; Yantis & Jones, 1991; Yantis & Jonides, 1984, 1990; Yantis & Hillstrom, 1994; Theeuwes, Kramer & Atchley, 1998); or the attentional prioritization of (new) search objects on the basis of top-down suppression of (old) distractor objects (visual marking; Watson & Humphreys, 1997, 1998, 2000; Watson, Humphreys, & Olivers, 2004).

The present experiments may help to specify some of the mechanisms mentioned here. For instance, Pylyshyn (2001, p.141) has argued that “...visual indexes could in principle be implemented by activation or inhibition of object representations...”. In this way, the results of the experiments reported here can be interpreted as evidence that visual indexes are in fact implemented in the inhibition of search display objects in parallel visual search. However, since inhibition was observed at more than five distractor locations, some additional mechanism beside the visual indexes must be at play. Further, our results generally agree with the idea of an overall saliency map (e. g., Wolfe et al., 1989), which function is to guide attention to locations in the visual field characterized by a high saliency. Although such a mechanism does not explicitly assume the inhibition of search distractors (cf. Treisman & Sato, 1990), it assumes the prioritized processing of target rather than distractor attributes which could lead to a decrement in the processing of distractor objects.

In contrast, the present findings rule out attentional control in parallel visual search to be due to the prioritization of new relative to old elements (e.g., Yantis & Jonides, 1984). However, they support the existence of visual marking (Watson & Humphreys, 1997), which is a inhibitory top-down mechanism of prioritizing processing of new by de-prioritizing of old stimuli. It remains an open issue, to be resolved in future research, how these various mechanisms can be integrated in a unified model of attentional prioritization.

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Epilogue

Epilogue

Although this thesis has reached its end, I have continued to think about other related issues. For example, some of my current thoughts are motivated by the controversy concerning the role of ‘memory’ in visual search, which started with Horowitz and Wolfe's (1998), who claimed that visual search is memory-less.

In one particular experiment (Horowitz and Wolfe, 1998), participants were engaged in the search for the letter "T" amongst differently oriented letters "L" in two different search conditions. In the dynamic search condition the search objects changed their positions every 111 ms. In the static search condition, whose role was to serve as the baseline-condition, the search objects remained at their position throughout the trial. Monte Carlo simulations of a serial sampling model demonstrated that the slopes of the response times (RTs) x display-size functions in the dynamic condition had to be twice as steep as in the static condition, if search were memory-less (i.e., previously visited objects/locations were re-sampled). Interestingly, the authors found no differences in the search performance between the dynamic- and static-conditions (as indexed by the slopes of the RT x display-size functions) indicating that there is no role for memory in visual search.

However, subsequent studies did not support this strong claim. For example, the results of von Mühlenen et al. (2003) argued that the two search conditions were different in terms of the used search strategies, thus, one cannot easily assume visual search to be memory-less. For the dynamic condition it was demonstrated that participants used a sit-and-wait strategy, that is, that they directed focal attention to a limited area of the display and waited for the target to appear there. In contrast, search performance in the static condition could be best explained by a serial search mechanism.

Momentarily, I further investigate such sit-and-wait strategies in dynamic visual search. In one experiment participants’ eye-movements were recorded while they were engaged in a dynamic- and a static search condition similar to that of Horowitz and Wolfe

(1998). It was found that the slopes of the RTs x display-size functions in the two search conditions were similar to those reported by Horowitz and Wolfe. However, with respect to eye-movement measures, in the dynamic condition relative to the static condition the average number of saccades and fixations was decreased by 73%, or 82%, respectively, and the fixation duration was increased by 51%. This reduction in eye movement is consistent with the sit-and-wait account. It should be noted that on the basis of these findings, it was not possible to infer the deployment of attention in dynamic visual search displays directly, because attention and eye-movements do not necessarily coincide (Schneider & Deubel, 1995). Because of this reason, in a further (gaze-contingent) experiment, I will probe currently fixated or non-fixated item-regions in dynamic visual search displays (e.g., one of the four quadrants of the visual search display) and will compare RTs to probes at previously fixated with probe-RTs at previously non-fixated item-regions. If attention and eye-movement are coupled in dynamic visual search, then the last visited item region should be inhibitorily tagged (Klein, 1988) and probe-RTs at previously fixated regions should be slower than probe-RTs at previously non-fixated regions. This result then would provide evidence a direct hint for the coupling of attention and eye-movements in dynamic visual search displays.

Moreover, if the sit-and-wait provides the best strategy in a dynamic physical world, and the serial inspection of search objects/locations in a static world without any moving stimuli, then the question arises when the sit-and-wait strategy switches to a serial inspection of search objects/locations or vice-versa. In the dynamic conditions of the experiment reported above, the search items changed their positions every 116.6 ms. But what will happen if participants have enough time (e.g., 150 to 300 ms) to make a fixation to one of the search objects/locations? Will they keep on waiting for the target to appear at the momentarily fixated item-region or will they start to serially scan the search objects/locations in order to find the target? Previous results demonstrated that search behavior depends not only on the amount of time the visual display is visible, but also on the search stimuli themselves (von

Mühlenen & Müller, 2001). However, it is of particular interest whether participants will accommodate their search behavior by the time the (dynamic) visual display remains visible for longer periods of time. Thus, in further experiments I will investigate the temporal characteristics of the sit-and-wait strategies in dynamic visual search more exhaustively.

In another line of research that is related to this topic I have looked at to what extent automatic priming of features can be influenced by top-down control (Maljkovic & Nakayama, 1994; McCarley & He, 2001). Maljkovic and Nakayama (1994) found that priming of features could not be influenced by conscious effort. In their Experiment 4, participants responded to the shape of a color-singleton target, which changed its color predictably in every second trial. In the active condition, participants should subvocally name the color of the target in the upcoming trial, that is, they should actively take advantage from the predictability of the color sequence. In the passive condition, participants should only respond to the shape of the color-singleton target. It was hypothesized that if priming is influenced by conscious efforts, then (automatic) priming should be diminished in the active relative to the passive condition because in the active condition participants could anticipate a change in the defining color of the target. Interestingly, the authors found that performance did not differ much between the two search conditions indicating that priming of features is impenetrable by top-down control.

In contrast to Maljkovic and Nakayama (1994), Müller and his colleagues (Müller et al., 2004) found evidence for a (autonomous) memory effect that was modulated by top-down processes. In a feature search task, the target (which was present on half of the trials) was either unique in color (red or blue) or unique in orientation (left-oblique or right-oblique). Participants' task was to respond to the presence or absence of the uniquely defined target. Mean response times were faster when the feature (e.g., red/red) or the dimension (e.g., color/color) of the target was repeated relative to when they were not repeated (e.g., color/orientation or orientation/color). Further, when participants were asked to report the target-defining dimension or feature on some proportion of trials, the (dimensional-specific) intertrial facilitation was increased relative to a no-memory condition, in which participants were never asked to report the target defining dimension or feature. With other words, although (autonomous) priming can produce an RT advantage, this RT benefit was increased by factors associated with the task procedure, namely the necessity to actively encode the target dimension or feature.

With reference to the findings of Müller et al. (2004), it is reasonable to conclude that although participants in the active condition of Experiment 4 (Maljkovic & Nakayama, 1994) were enforced to take advantage of the predictability of the color sequence by subvocally name the color of the target in the next trial, they could have ignored this regularity because the target could also be easily detected without drawing attention to the predictably changing color sequence. Thus, there may have been insufficient power for a top-down effect to emerge. Therefore, with respect to the question whether the priming of features can be influenced by conscious effort in a two-alternating color sequence it could be more beneficial to ask participants for the target-defining color (Müller at al., 2004) rather than to enforce them to subvocally name the color of the target in the next trial (Maljkovic & Nakayama, 1994). However, despite the role of the ‘response-demands’ of a search task, there are more reasons, why Maljkovic and Nakayama could have failed to reveal evidence for a top-down modulable (autonomous) memory effect: First, since the authors have used a compound-task, in which the attention-relevant feature (color) was dissociated from the response-relevant feature (shape), it remains the possibility that while top-down influences can be demonstrated in a feature-search task (where the attention- and response-relevant features conincide; Müller et al.), it cannot be demonstrated with compound-tasks (Maljkovic & Nakayama). Second, a related reason could be that while dimension-specific intertrial facilitation is top-down influenceable (Müller et al.), feature-specific facilitation is not (Maljkovic and Nakayama).

In a new experiment I have used a two-alternating sequence, in which the target-defining dimensions (color/orientation) and not its features (red/blue; left-oblique /right-oblique) changed predictably every second trial. On some proportion of trials, participants were either asked for the target defining dimension (dimension-memory condition), the target defining feature (feature-memory condition), or they were not asked at all (no-memory condition). These questions were always inserted after the second trial of similarly defined dimension targets. It was hypothesized that if priming can be influenced by conscious effort, dimension-specific intertrial facilitation should be reduced in the dimension- and feature-memory conditions, because queries were inserted to enforce participants to take advantage of the predictably changing sequence. However, first results show that dimension-specific intertrial facilitation in the dimension- and feature-memory conditions did not stand out against the (dimension-specific) facilitatory effect in the no-memory condition. At the first glance, this pattern of results would suggest that autonomous priming is top-down impenetrable[influenced?]. However, since overall RTs were comparable between the three conditions, this makes it very likely that in the dimension- and feature-memory conditions, the need to actively encode the target's relevant attributes had only limited influence on autonomouspriming. In other words, this means that participants were able to answer the dimension or feature queries on the basis of the regularly changing sequence alone. Thus, in order to demonstrate top-down modulation of (autonomous) priming, further experiments will be necessary that make the additional task requirements more effective.

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Zusammenfassung

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Im experimentellen Paradigma der visuellen Suche besteht die Aufgabe der Probanden darin, die An- bzw. Abwesenheit eines Zielreizes („Target“), welcher zusammen mit Störreizen („Distraktoren“) dargeboten wird, anzuzeigen. Die Gesamtanzahl von Suchobjekten (Target und Distraktoren) wird als Display-Größe bezeichnet und ein Target wird gewöhnlich in 50% aller Durchgänge dargeboten. Die interessierenden abhängigen Variablen sind die Reaktionszeit (RT), d.h. wie lange es dauert bis eine an- bzw. abwesend Reaktion abgegeben wird und die Genauigkeit der Probanden, d.h. ob das Target korrekt identifiziert wurde. Stellt die RT die abhängige Variable dar, dann bleiben die Suchobjekte sichtbar bis die Probanden reagieren und anhand der funktionalen Abhängigkeit zwischen der Anzahl der Suchobjekte im Display (Abszisse) und der RT der Probanden (Ordinate) kann auf die zugrundliegenden Suchmechanismen geschlossen werden. Stellt dagegen die Genauigkeit der Probanden die abhängige Variable dar, dann wird das Suchdisplay nach einer bestimmten Zeit durch einen Maskierungsreiz ersetzt. Die Zeit zwischen dem Abschalten des Suchdisplays und der Darbietung des Maskierungsreizes wird als Interstimulus-Intervall (ISI) bezeichnet und anhand der funktionalen Abhängigkeit zwischen ISI (Abszisse) und Genauigkeit der Probanden (Ordinate) kann auf die zugrundeliegenden Suchmechanismen geschlossen werden.

Für den Fall das sich das Target durch ein einzelnes Merkmal von den Distraktoren unterscheidet (z.B. rotes Target und grüne Distraktoren), finden sich sehr flache Anstiege, d.h. zwischen 0 und 10 Millisekunden (ms) pro Suchobjekt (Wolfe, 1998), der RT x Display-Größe Funktionen. M. a. W. ist die RT nahezu unabhängig von der Anzahl der Objekte im Display. Dies zeigt sich auch im Zusammenhang der Analyse der Genauigkeit der Probanden: So kann das Target in dem Fall, in dem es sich in einem Merkmal von den Distraktoren unterscheidet bereits bei sehr kurzen ISI’s entdeckt werden. Diese Form visueller Suche wird auch als parallele Suche bezeichnet und als Hinweis angesehen, dass das Target schnell bzw.

präattentiv entdeckt werden kann. Ist das Target dagegen definiert durch eine Kombination von Merkmalen (z.B. horizontal-rotes Target und vertikal-rote und horizontal-grüne Distraktoren; sog. Konjunktionssuche), sind deutlich längere ISI's notwendig, d.h. ca. 40 bis 50 ms pro Displayobjekt (Wolfe, 1998), um das Target korrekt zu entdecken. Im Zusammenhang der RT zeigt sich häufig eine Dissoziation zwischen Durchgängen in denen das Target an- oder abwesend ist. Im Fall der Anwesenheit des Targets finden sich Anstiege der Suchfunktionen von ca. 20 bis 30 bzw. von 40 bis 60 ms pro Suchobjekt wenn das Target abwesend ist (Wolfe, 1998). Dies wird angesehen als Ausdruck eines seriellen Suchmechanismus, d.h. dass davon ausgegangen wird, dass die einzelnen Suchobjekte hintereinander abgesucht werden bis das Target entdeckt wird, da es Eigenschaften mit den Distraktoren gemeinsam hat. Dabei müssen im Falle der Anwesenheit des Targets jedoch nur 50% der Suchobjekte abgesucht werden, da es im statistischen Mittel bereits nach der Hälfte der abgesuchten Objekte gefunden wird. Dagegen müssen in Target-abwesend Durchgängen alle Objekte abgesucht werden, um eine korrekte Entscheidung bzgl. der Abwesenheit des Zielreizes zu machen.

Die Unterscheidung von parallelen und seriellen Suchmechanismen geht stark auf die ursprüngliche Form der Merkmalsintegrationstheorie von Treisman und Gelade (1980) zurück. Die Merkmalsintegrationstheorie (MIT) beschreibt die visuelle Objektwahrnehmung als zweistufigen Prozess, wobei auf der ersten Stufe der visuellen Informationsverarbeitung (der sog. präattentiven Stufe) die elementaren Attribute von Objekten (z.B. deren Farbe oder Orientierung) in dimensionsspezifischen, aber distinkten Merkmalskarten verarbeitet werden (so existieren für Farbe separate Merkmalskarten für rot, grün, usw. und für Orientierung separate Merkmalskarten für horizontal, vertikal, usw.). In einem zweiten Verarbeitungsschritt, der Stufe der gerichteten Aufmerksamkeit, werden die Informationen aus den einzelnen Merkmalskarten zu einem ganzheitlichen Objekt zusammengefügt. Dies geschieht mittels der sog. Masterkarte der Objektlokationen, in welcher die Information über die Position eines Objektes verarbeitet wird und über welche die Merkmale eines Suchobjektes, durch Ausrichtung von visueller Aufmerksamkeit auf die Position des Objektes, integriert werden können. Wenn sich das Target in nur einem Merkmal von den Distraktoren unterscheidet, dann ist die Aktivität innerhalb einer einzigen Merkmalskarte stark und visuelle Aufmerksamkeit kann direkt auf die Position des Targets gerichtet werden, so dass es präattentiv entdeckt werden kann. Ist das Target jedoch durch eine Kombination von Merkmalen definiert, dann sind mehrere Merkmalskarten aktiviert, bzw. reicht die Aktivität innerhalb einer einzelnen Merkmalskarten nicht aus, um fokale Aufmerksamkeit direkt auf die Position des Targets zu lenken. Um das Target korrekt zu entdecken ein serielles Inspizieren der Suchobjekte, auf der Stufe gerichteter Aufmerksamkeit, notwendig.

Jedoch bestreiten in der Zwischenzeit eine Reihe von Autoren (z.B. Duncan & Humphreys, 1989) die Unterscheidung von parallelen und seriellen Suchprozessen und postulieren, dass im Prinzip alle Suchprozesse parallel ablaufen können bzw. das es ein Kontinuum von Suchprozessen, hinsichtlich ihrer Effizienz, gibt. Im Kern unterscheidet sich die Ähnlichkeitstheorie der visuellen Suche von Duncan und Humphreys (1989; 1992) grundlegend von der MIT und zwar dahingehend, dass die visuelle Szene auf der ersten Stufe der Verarbeitung in sog. strukturellen Einheiten repräsentiert wird. Diese strukturellen Einheiten sind hierarchisch aufgebaut, d.h. dass eine Repräsentation oder strukturelle Einheit in immer feinere Einheiten gegliedert ist (z.B. könnte der Buchstabe F, als strukturelle Einheit, auf der nächstkleineren Hierarchieebene als horizontale und vertikale Linien repräsentiert sein). Eine der Hauptannahmen der Ähnlichkeitstheorie ist, dass strukturelle Einheiten nach dem Prinzip der Ähnlichkeitsgruppierung gebildet werden, d.h. dass einzelne Elemente der visuellen Szene, beispielsweise hinsichtlich der Farbe, Form oder Größe, zu strukturellen Einheiten zusammengefasst werden können. Im Zusammenhang der visuellen Suche umfassen Gruppierungsprozesse jedoch nicht nur die Ähnlichkeit zwischen Target und Distraktoren, sondern auch die Ähnlichkeit zwischen den Distraktoren selbst. So konnten

Duncan und Humphreys (1989) in einer Reihe von Experimenten zeigen, dass die Suche effizient war, wenn die Ähnlichkeit zwischen Target und Distraktoren (T-D Ähnlichkeit) niedrig war. War dagegen die Ähnlichkeit zwischen Target und Distraktoren hoch, dann war die Sucheffizienz stark abhängig von der Ähnlichkeit der Distraktoren untereinander (D-D Ähnlichkeit). Somit nehmen die Autoren keine distinkten parallelen und seriellen Suchprozesse an, vielmehr unterscheidet sich die Effizienz von Suchaufgaben ihrer Meinung nach darin, inwieweit das Target (T-D Ähnlichkeit) und die Distraktoren (D-D Ähnlichkeit) als distinkte strukturelle Einheiten wahrgenommen werden können.

Neben diesen Faktoren der visuellen Szene, d.h. der Anzahl der Suchobjekte bzw. deren Ähnlichkeit untereinander, berücksichtigen neuere Erklärungsansätze auch andere Aspekte die das zielgerichtete Durchmustern des Suchdisplays ermöglichen. Dazu zählen hemmende und fördernde Gedächtnismechanismen, die einzelne Distraktoren von der Suche ausschließen bzw. die Verarbeitung des Targets beschleunigen können. Diese verschiedenen Gedächtnismechanismen können entweder willkürlich („top-down“) oder unwillkürlich („bottom-up“) gesteuert sein bzw. können sie über die Hemmung (Inhibition) oder Förderung (Erleichterung) von Positionen, Merkmalen, Dimensionen (z.B. Farbe oder Orientierung) oder über die Suchobjekte selbst wirken. Darüber hinaus können sich diese Gedächtnismechanismen im Bereich von Millisekunden, über Sekunden, bis hin zu Stunden und Jahren manifestieren (Shore & Klein, 2000).

Gegenwärtig werden insbesondere im Zusammenhang mit kurzfristigen Gedächtnisprozessen (Millisekunden) eine Reihe alternativer Mechanismen diskutiert. Dazu zählen u.a. der erstmals von Posner und Cohen (1984) beschriebene inhibitorische Mechanismus des „Inhibition of Return“ (IOR), d.h. dass die Entdeckung eines Targets verlangsamt ist, wenn es 300 ms (oder später) im Anschluss an die Darbietung eines Hinweisreizes an dessen Position erscheint. Klein (1988) konnte den IOR-Effekt auch in einem visuellen Suchparadigma nachweisen. Dabei konnte er zeigen, dass die im Verlauf der

Suche inspizierten Distraktoren mittels IOR aktiv gehemmt werden können. Dieses Resultat zeigt, dass durch IOR die Wahrscheinlichkeit eines erneuten Absuchens von Suchobjekten minimiert bzw. als Folge, die Sucheffizienz maximiert werden kann. In der Folgezeit gab es zahlreiche Versuche in denen Kleins ursprüngliche Resultate nicht repliziert werden konnten (z.B. Wolfe & Pokorny, 1990; Klein & Taylor, 1994), jedoch konnten Takeda und Yagi (2000) bzw. Müller und von Mühlenen (2000) zeigen, dass das Auftreten von IOR von ganz spezifischen Displayeigenschaften abhängig ist. Hierzu zählt beispielsweise das der „Probe-Stimulus“, bei welchem es sich um einen einfachen visueller Reiz handelt der im Anschluss an die Suchreaktion an spezifischen Orten des Suchdisplays (z.B. den Distraktoren) dargeboten wird und anhand dessen der IOR-Effekt abgeschätzt werden kann, gleich häufig an freien Stellen des Suchdisplays bzw. an der Position von Distraktoren präsentiert wird (Müller & von Mühlenen, 2000).

Ein ähnlicher Mechanismus der Hemmung einzelner Displayobjekte ist die visuelle Markierung („Visual Marking“), durch welche sowohl einzelne Suchobjekte selbst (Watson & Humphreys, 1997) bzw. deren Eigenschaften (Watson & Humphreys, 1998) von der weiteren Verarbeitung ausgeschlossen werden können. Im Unterschied zu IOR, durch welchen die Positionen der Suchobjekte (Klein, 1988) oder die Suchobjekte selbst (z.B. Tipper, Driver und Weaver, 1991) gehemmt werden, handelt es sich bei der visuellen Markierung um einen zeitlichen Hemmungsmechanismus, d.h. dass Merkmale oder Objekte der visuellen Szene auf der Basis ihrer zeitlichen Darbietung im Suchdisplay von der weiteren Verarbeitung ausgeschlossen werden. In diesem Zusammenhang konnten Watson und Humphreys (1997) zeigen, dass ein Teil der Suchobjekte, welcher 400 ms vor dem Erscheinen eines weiteren Teils von Suchobjekten dargeboten wurde, visuell markiert oder von der weiteren Suche ausgeschlossen werden konnte.

Mittelfristige erleichternde und inhibitorische Gedächtnisprozesse manifestieren sich im Bereich von Sekunden. So zeigte sich in einer einfachen Farb-Entdeckungsaufgabe, dass die Wiederholung von Target-Farbe oder -Position die RT auch noch nach 30 Sekunden, d.h. nach 5 bis 8 Durchgängen, beschleunigen kann (Maljkovic und Nakayama, 1994; 1996). Interessanterweise waren die Probanden in dieser Aufgabe jedoch nicht in der Lage, die Farbe oder Position des Targets aus vorangegangenen Durchgängen zu berichten (Maljkovic und Nakayama, 2000). Auch konnten die Autoren zeigen, dass typische RT-Kosten, die bei einem Wechsel der Targetfarbe von einen auf den anderen Durchgang auftreten, selbst dann nicht reduziert waren, wenn die Probanden einen Farbwechsel antizipieren konnten, d.h. wenn sie wussten, dass die Farbe des Targets alle 2 Durchgänge wechselte (Maljkovic und Nakayama, 1994; Experiment 4). Diese Befunde interpretierten Maljkovic und Nakayama (1994; 1996) dahingehend, dass merkmals- (Farbe) bzw. positionsspezifische Gedächtnismechanismen bottom-up (automatisch) wirken, m. a. W., dass sie willentlich nicht beeinflussbar sind.

Jedoch stammen konträre Befunde aus den Experimenten Müller, Krummenacher und Heller (2004). So war der typische Erleichterungseffekt bei Wiederholung von Target-Merkmal oder -Dimension (Müller, Heller und Ziegler, 1995) in einer einfachen Farb- oder Orientierungsentdeckungsaufgabe, in der die Probanden zusätzlich zur Entdeckung des Targets auch noch dessen Attribute (Farbe oder Orientierung) enkodieren sollten, relativ zu einer Kontrollbedingung (in der die Probanden niemals die Attribute von Targets enkodieren sollten), erhöht. Obwohl also die Wiederholung von Target-Merkmal oder –Dimension zu einer Erleichterung führen kann (angezeigt durch die Kontrollbedingung), ist dieser Erleichterungseffekt größer, wenn die Probanden zusätzlich die Attribute des Targets memorieren sollen, was die Autoren als Ausdruck der (aufgabenspezifischen) top-down Beeinflussbarkeit von Gedächtnisprozesse werteten.

Auf den ersten Blick sprechen diese widersprüchlichen Befunde für unterschiedliche Gedächtnismechanismen – automatisch und merkmalsspezifisch (Maljkovic und Nakayama, 1994; 1996) bzw. willentlich beeinflussbar und dimensionsspezifisch (Müller und Kollegen, 2004). Jedoch stammen ähnliche Ergebnisse wie die von Müller und Kollegen (2004) aus den

Experimenten von Hillstrom (2000). So waren in einer einfachen Farbentdeckungsaufgabe (Hillstrom, 2000; Experiment 1), in der die Target-Farbe entweder alternierend alle 2 Durchgänge (gleiche Prozedur wie Maljkovic und Nakayama 1994; Experiment 4) oder zufällig wechselte (zufällige Bedingung), die RT in der alternierenden, relativ zur Zufallsbedingung, um 115 ms verkürzt. Darüber hinaus fanden sich keine Unterschiede in der RT zwischen alternierender und Zufallsbedingung, wenn in einer Merkmals- (Experiment 3) oder. Konjunktionsaufgabe (Experiment 4) ein zusätzliches Target dargeboten wurde. Dabei wussten die Probanden in beiden Experimenten (Experiment 3 und 4), anhand eines akustischen Signals, wie das Target im jeweils nächsten Durchgang definiert war. Diese Befunde aus einer Vielzahl von Suchaufgaben (Merkmals- und Konjunktionssuche) wertete Hillstrom als Ausdruck dafür, dass (merkmalsspezifische) Gedächtnisprozesse top-down beeinflussbar sind. Zusätzlich fand Hillstrom in Experiment 4, dass die Wiederholung der Targeteigenschaften nicht die Suchzeiten pro Displayobjekt (im Sinne des Anstiegs der RT x Display-Größe Funktionen), sondern die Basisperformanz (im Sinne des Ordinaten-Schnittpunktes der RT x Display-Größe Funktionen) beeinflusste. Auf der Basis dieses Befundes schlug die Autorin einen Mechanismus der „Prioritisierung“ vor, d.h. dass die (merkmalsspezifischen) Erleichterungseffekte bei Wiederholung der Targetmerkmale in aufeinanderfolgenden Durchgängen aus der beschleunigten Verarbeitung der Target-definierenden Attribute (z.B. Farbe, Orientierung) resultieren.

Jedoch sind prinzipiell auch andere Mechanismen denkbar, wie die Erleichterungseffekte zustande kommen können. Zum Beispiel nehmen Kristjànsson, Wang und Nakayama (2002; Wang, Kristjánsson & Nakayama, 2001) an, dass die Erleichterungseffekte aus der wiederholten Darbietung der Distraktor- und nicht der Targeteigenschaften, im Besonderen aus der schnelleren perzeptuellen Gruppierung der Distraktoren und der damit verbundenen schnelleren Target an- bzw. abwesend Reaktion vor dem Hintergrund homogen-gruppierter Distraktoren, resultieren. Basis dieses alternativen

Erklärungsansatzes sind Befunde, wonach die Autoren, selbst in Target-abwesend Durchgängen, Evidenzen für verkürzte RT fanden, wenn die Eigenschaften der Distraktoren in aufeinanderfolgenden Durchgängen konstant waren. Jedoch ist es, insbesondere in Target-anwesend Durchgängen auch vorstellbar, dass der Erleichterungseffekt aus der alleinigen Wiederholung der Target- und nicht der Distraktoreigenschaften, resultiert. Diese Fragestellung konnte jedoch durch die von Kristjánsson und Kollegen (2002) eingesetzten Methodik nicht beantwortet werden.

Langfristige Gedächtnisprozesse (Stunden bis Jahre) in visueller Suche konnten in zahlreichen Arbeiten, z.B. von Chun und Jiang (1998), nachgewiesen werden. Dabei besteht das grundlegende Vorgehen in diesen Arbeiten darin, das identische Suchdisplays (konsistente Bedingung) während der gesamten Dauer des Experiments wiederholt werden können. Die RT in der konsistenten Bedingung werden im Anschluss mit den RT in der inkonsistenten Bedingung, d.h. in einer Bedingung, in der die Suchobjekte ihre Eigenschaften wechseln, verglichen. Üblicherweise zeigt sich, dass die RT in der konsistenten Bedingung schneller ist als in der inkonsistenten Bedingung, was als Ausdruck eines Gedächtnisses für die Eigenschaften der Suchobjekte in der konsistenten Bedingung interpretiert wird.

Im Rahmen dieser Arbeit wurden die kurz- (Millisekunden) und mittelfristigen Einflüsse (Sekunden) des Gedächtnisses auf die visuelle Suchleistung, im Besonderen die Zusammenhänge zwischen positions-, merkmals- und objektspezifischen Gedächtnismechanismen und Suchperformanz untersucht. Kapitel 2 widmet sich den Beziehungen zwischen positionalem Gedächtnis und Suchleistung und Kapitel 3 dem Einfluss merkmalsbasierter Gedächtnismechanismen in visueller Suche. In Kapitel 4 wurde ein alternativer Gedächtnismechanismus für die Hemmung von Distraktorobjekten untersucht.

Wie in der Arbeit von Maljkovic und Nakayama (1996) gezeigt werden konnte, beeinflusst die Wiederholung der Targetposition systematisch die Entdeckung des Targets: Wurde die Position des Targets wiederholt, dann war die RT reduziert (Erleichterung); wurde dagegen das Target auf der Position eines vorherigen Distraktors dargeboten, dann war die RT verlangsamt (Inhibition). Aufbauend auf diesen Befunden wurde in Kapitel 2 die zeitliche und räumliche Dynamik positionsspezifischer Gedächtnisprozesse weiter untersucht. Dazu wurde die Anzahl der Suchobjekte (Distraktoren) systematisch variiert und überprüft, ob sich diese Manipulation in den inhibitorischen Effekten widerspiegelt wenn der Zielreiz auf der Position eines Distraktors aus einem vorangegangenen Durchgang dargeboten wurde. Die Ergebnisse zeigten Evidenzen für förderne und hemmende Gedächtnisprozesse, wobei sich die Erleichterungseffekte als unabhängig von der Anzahl der Suchobjekte (entweder 3, 4, 6 oder 8) erwiesen, die Hemmungseffekte jedoch nur bei einer Display-Größe von 3 Objekten (ein Target und zwei Distraktoren) nachgewiesen werden konnten. Der letztere Befund wurde als Ausdruck einer Limitierung des positionalen Gedächtnisses gewertet, wobei die differentiellen Erleichterungs- und Hemmungseffekte die Annahme distinkter Einheiten für Target- und Distraktorpositionen nahe legten. Darüber hinaus erwiesen sich die Erleichterungs- und Hemmungseffekte, insbesondere bei einer Display-Größe von 3 Suchobjekten, als sehr stark übungsabhängig: So waren die Effekte im letzten, gegenüber dem ersten Drittel des Experiments, deutlich stärker ausgeprägt. In einem weiteren Experiment, in dem die Erleichterungs- und Hemmungseffekte bei Anwesenheit von 3 Suchobjekten untersucht wurden, konnte gezeigt werden, dass die Formation des positionalen Gedächtnisses sehr stark abhängig ist von der Anordnung der Suchobjekte in aufeinanderfolgenden Durchgängen. So fanden sich keine Beweise für Erleichterungs- und Hemmungseffekte, wenn die Anordnung der Suchobjekte zwischen einzelnen Durchgängen zufällig wechselte.

In Kapitel 3 wurden merkmalsbasierte Gedächtnisprozesse in Konjunktionssuchaufgaben (Farbe x Orientierung) untersucht, d.h. ob die Erleichterungseffekte für das erneute Darbieten identischer Suchobjekte aus der Wiederholung von Target- oder Distraktoreigenschaften resultieren (Kristjánsson und Kollegen, 2002). Zu diesem Zweck wurden in einer Reihe von Experimenten jeweils zwischen zwei benachbarten Durchgängen entweder die Eigenschaften des Targets und der Distraktoren, des Targets allein oder der Distraktoren allein wiederholt dargeboten und mit einer Baseline-Bedingung, in welcher die Merkmale des Targets und der Distraktoren zwischen einzelnen Durchgängen wechselten, verglichen. Die Ergebnisse zeigten, dass die RT bei gleichen Target- und Distraktoreigenschaften und gleichen Target- oder Distraktoreigenschaften relativ zur Baseline-Bedingung beschleunigt waren, was durch das Wirken eines Gedächtnisses für die Merkmale der Suchobjekte erklärt wurde. Jedoch war die RT langsamer, wenn nur die Targeteigenschaften allein relativ zu den Target- und Distraktoreigenschaften oder den Distraktoreigenschaften allein wiederholt präsentiert wurden. Zusätzlich unterschieden sich die RT bei Präsentation identischer Target- und Distraktoreigenschaften und der alleinigen Wiederholung der Distraktoreigenschaften nicht. Mit anderen Worten war der RT-Vorteil jeweils größer, wenn die Eigenschaften aller Suchobjekte (Target und Distraktoren) oder der Distraktoren allein im Gegensatz zu den Targeteigenschaften wiederholt wurden. Dieses Muster der Resultate wurde dahingehend interpretiert, dass erleichternde Gedächtnisprozesse in Konjunktionssuchaufgaben auf der Wiederholung der Distraktoreigenschaften basieren. Zusätzlich konnte gezeigt werden, dass die Gedächtnismechanismen über die Wiederholung von Subgruppen von Distraktoren, insbesondere der Distraktoren die die Farbe und nicht die Orientierungs des Targets teilen, laufen.

In Kapitel 4 sollte überprüft werden, ob sich inhibitorische und kurzfristige (Millisekunden) Gedächtnismechanismen auch in einfachen Merkmalsentdeckungsaufgaben manifestieren. Eine Möglichkeit der Überprüfung hemmender Gedächtnismechanismen ist die Präsentation eines „Probe-Stimulus“ an freien Positionen des Displays („Off-Probe“) oder an den Positionen der Suchdistraktoren („On-Probe“) im Anschluss an die Target-anwesend oder -abwesend Reaktion der Probanden. Da jedoch die Reaktion auf einen Reiz, insbesondere auf einen Probe Stimulus, auch durch die Maskierung der vorangegangenen Suchobjekte negativ beeinflusst werden kann (Breitmeyer, 1984), wurden die Probe-RT aus der Entdeckungsaufgabe mit den Probe-RT aus einer zweiten Aufgabe, in welcher die Probanden die Suchdisplays nur passiv betrachtet und nicht abgesucht haben, verglichen. Durch den Vergleich der differentiellen RT zwischen On- und Off-Probes in der Entdeckungs- und Passivaufgabe konnte die tatsächliche Hemmung, bereinigt um Maskierungseffekte, geschätzt werden. In einer Reihe von Experimenten wurden Evidenzen für die Hemmung der Suchdistraktoren gefunden. Diese Hemmung war jedoch abhängig von spezifischen Displayeigenschaften: So konnte keine Hemmung nachgewiesen werden, wenn die Suchdisplays im Anschluss an die Reaktion der Probanden, und vor der Präsentation des Probe-Stimulus, abgeschaltet wurden. Dieses Resultat wurde dahingehend interpretiert, dass die Hemmung der Distraktoren objekt- und nicht positionsspezifisch ist. Weiterhin war die Hemmung der Distraktorobjekte verringert, wenn deren Helligkeiten vor der Präsentation der Probe-Stimuli reduziert wurden. Diese Reduzierung der Hemmung veränderter Distraktoren konnte nicht durch die attentional-prioritäre Verarbeitung (Yantis & Jonides, 1984) erklärt werden. Auch war die Hemmung einzelner Distraktorobjekte nachweisbar, wenn die Augenbewegungen der Probanden kontrolliert wurden.

Zusammenfassend unterstützen die Ergebnisse dieser Arbeit die Existenz erleichternder und inhibitorischer Gedächtnismechanismen in visueller Suche. In Merkmalsentdeckungsaufgaben konnte über Durchgänge hinweg gezeigt werden, dass die räumliche Kapazität positionsspezifischer Erleichterungs- und Hemmungseffekte begrenzt sowie deren Manifestation abhängig von der räumlichen Anordnung der Suchobjekte ist. In Konjunktionssuchaufgaben konnte gezeigt werden, dass die erleichternden (merkmalsbasierten) Gedächtniseffekte, über Durchgänge hinweg, aus der Wiederholung spezifischer Distraktor- und nicht der Targetmerkmale resultierten. Evidenzen für objekt-spezifische und inhibitorische Gedächtnismechanismen konnten in einer Merkmalsentdeckungsaufgabe, innerhalb einzelner Durchgänge, nachgewiesen wurden. Dabei erwies sich die Hemmung einzelner Distraktorobjekte als abhängig von spezifischen Eigenschaften des Suchdisplays (z.B. dass die Suchobjekte zum Zeitpunkt des Darbietens eines Probe-Stimulus noch sichtbar waren oder dass Veränderungen der Helligkeiten der Suchdistraktoren die mit ihnen assoziierte Hemmung reduzieren können).

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Curriculum Vitae

Curriculum Vitae

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