Accounting for priming in visual search
Episodic retrieval does not explain priming of pop-out

Árni Gunnar Ásgeirsson

HÁSKÓLI ÍSLANDS

Accounting for priming in visual search
Episodic retrieval does not explain priming of pop-out

Árni Gunnar Ásgeirsson

Ritgerð þessi er lokaverkefni til MSc gráðu í sálfræði og er óheimilt að afrita ritgerðina á nokkurn hátt nema með leyfi rétthafa.

Preface

This MSc. thesis (60 ECTS) in psychology was written under the guidance of Dr. Árni Kristjánsson. I want to thank Dr. Árni Kristjánsson, the examiner, the staff at the Department of Psychology and the many participants for their contributions to the thesis. Thanks to Maike Kathrin Aurich for her help with data collection for experiment 6.

Abstract

Pop-out visual search performance is not only influenced by bottom-up saliency but also by previous task history. If the target in such a task remains the same from one trial to the next performance is faster and more accurate than if the target identity changes (Maljkovic and Nakayama, 1994; Sigurdardottir *et al.*, 2008). Maljkovic and Nakayama argued that this reflects feature facilitation, that attention is drawn to the feature defining the target on the preceding trials. This conception is challenged in episodic retrieval accounts (Huang *et al.*, 2004; see also Hillstrom, 2000), where it is assumed that priming reflects a higher-level episodic memory representation of the search on the last trial. Here we show that the interaction between repetitions of different features critical for the episodic retrieval account applies only to a limited subset of tasks – in particular very difficult single-feature searches. We argue that feature facilitation is the most parsimonious accounts of priming of pop-out but episodic retrieval account have an important, albeit limited, in visual search. We conclude that a dual- or multi-stage account is needed to explain the heterogeneous results in the priming literature.

Table of contents

1   Introduction

Visual search is one of the most commonly used experimental paradigms in research on visual attention. A visual search task (VST) is a simulation of searching behavior in animals where the experimenter has full control of stimulus variables. In typical visual search the subject searches for an item, the target, among one or multiple items, the distractors. The experimenters collect the reaction times and response accuracy under different condition and confirm or reject their hypotheses accordingly. The vast majority of visual search tasks are presented on computer screens.

The most common types of questions answered by visual search data regard: (1) How we process visual stimuli, (2) how do we allocate our attentional resources, (3) what are the visual attributes that guide this allocation.

Visual search tasks can be categorized on a few dimensions. The most important classifications are the nature of the behavioral task (the response), the nature of the stimuli and the subject's foreknowledge of the target and/or the presentation contingencies. Some categorizations are also made in retrospect such as search efficiency defined by trends in the data rather than by features of the VST itself.

The nature of the task: When running a VST the experimental design will demand a response to the presented stimuli. There are two general kinds of responses in VSTs, detection and discrimination. The detection task only demands the subject to report whether a target is present in a visual search array. There will be one response signifying the presence (figure 1A) of a target and another to signify that no target is present (figure 1B). In a discrimination task the subject must detect the target in the search array but also report a visual attribute, e.g. whether a notch is cut off the left or right side of a diamond (figure 1C; see e.g. Maljkovic and Nakayama, 1994).

The nature of the stimuli. This dimension is more complicated than the type-of-task dimension and can be subcategorized. Firstly, any change in visual attributes may change responses to visual stimuli. A black target among white distractors will be easier to detect than a black target among grey distractors (fig 1D). Difficult discrimination in a VST will require different processing from a very easy discrimination, as one may require focal attention while the other will be detected, and perhaps discriminated, peripherally.

The difference between the target and distractors has a large effect on search behavior and this is the reason for the sub-categorization of feature vs. conjunction search tasks. In a feature search task a single feature will distinguish the target from the surrounding distractors. In some feature search tasks the defining feature will pop-out effortlessly and responses will be very fast while feature searches where the defining features are less salient can be quite difficult despite the single feature difference (figure 1D). In a conjunction task a target will share two or more features with two or more types of distractors, e.g. a vertical red bar serves as the target presented among green vertical bars and red horizontal bars (figure 1F).

Detection tasks

A: Target present   B: Target absent   C: Discrimination
                                                           task

D: Signal strength   E: Efficient vs. in-   F: Conjunction search
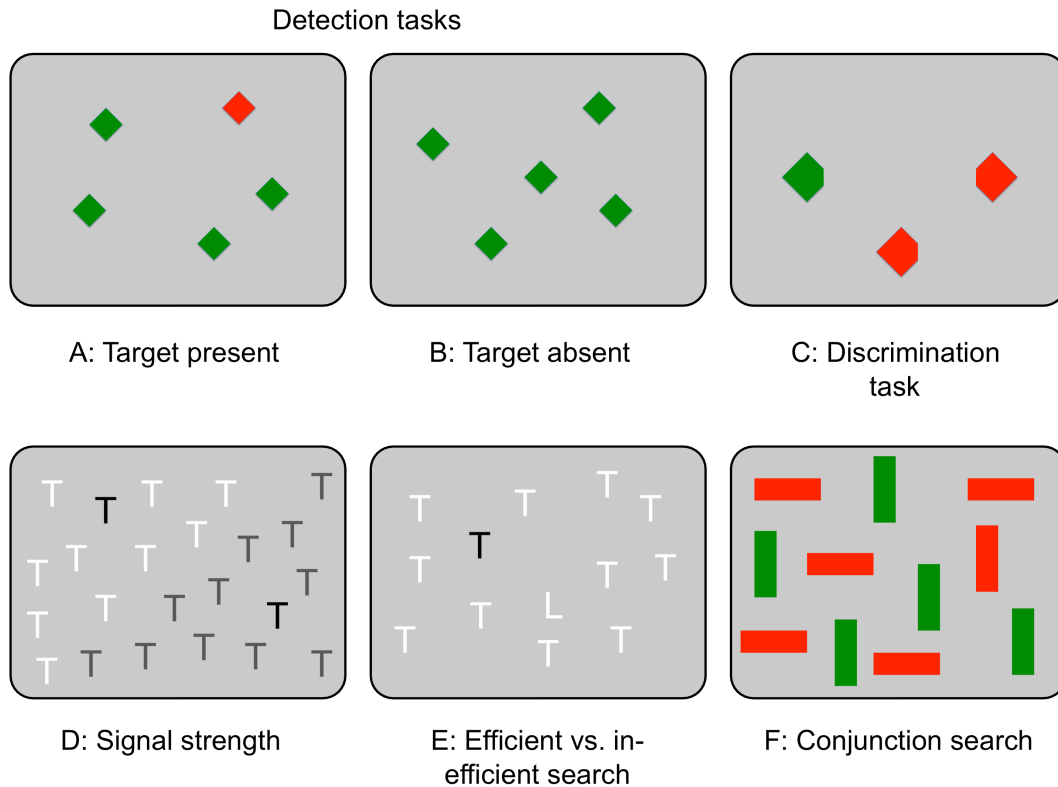   efficient search

Figure 1. Examples of stimuli commonly used in visual search. A: A red target is present among green distractors. B: No target is present on the screen. C: A green target is present among red distractors. Here the subject reports "right" because a notch has been cut off the right corner of the target diamond. D: Although both are feature searches the black T is much more salient among the white T distractors than among the grey ones. E: The black T and the white L can both serve as targets. While the T has the exact same shape as the distractors it still pops-out due to the difference in brightness. However, the L shares brightness with the distractors but differs in the less salient shape dimension. F: A vertical red target shares color with horizontal distractor and orientation with vertical green distractors.

The effects of conjunction vs. feature VSTs are most apparent on search slopes. A search slope is the time needed to process additional items in a search array. In efficient (pop-out) feature search tasks a search slope may be close to zero ms/item and sometimes even negative when distractor set size is small (Bravo and Nakayama, 1992; Meeter and Olivers, 2006). This is explained by the limited information in e.g. a 3-item search array (figure 1C). Adding items will increase the subject's certainty of target identity (e.g. color in figure 1C) and the subject will respond faster. In conjunction search the search slopes are positive, i.e. reaction times will increase for each item added to the search array. This is because the items cannot be distinguished on any single dimension, which means the subject may have to scan the array and evaluate many items before a target is found, or the subject decides that no target is present.

1.1 Proposed models of visual search

The first viable theory of visual search was the feature-integration theory (FIT) proposed by Treisman and Gelade (1980). Their model assumed that when presented with a feature search array the visual system would process the whole array in parallel and detect the target pre-attentively, since it would stand out on a given "feature-map". According to Treisman and Gelade (1980) a feature-map holds a pre-attentive registration of features in the visual field extracted from an initial parallel processing stage. Feature-maps are registered for each dimension of visual features i.e. color, orientation, shape, etc. During parallel processing the maps do not share any information between them. A singleton color target would thus stand out against items of a different color in the color map. During conjunction search the target is defined by a conjunction of features from at least two dimensions and is therefore not separable from the distractors using information from any single feature-map. Here we need focal attention to bind information from different maps together and this is managed only through serial processing. The subject would therefore need to serially check item after item until the target is found (self-terminating search). This model predicts that search slopes for target absent trials should be twice the slopes of target present trials, since subjects would on average have to evaluate half the items in a search array to find a target but all items to reject a target absent array (Treisman and Gelade, 1980).

Wolfe and colleagues challenged this view a decade later when they published a series of experimental data from conjunction search tasks inconsistent with feature-integration theory (Wolfe, Cave and Franzel, 1989). The most important anomalies found by Wolfe *et al.* were (1) that target-absent vs. target-present slope ratios were usually less than 2:1 suggesting that conjunction search was not strictly serial (although momentum of search could also explain this effect[1]) and (2) in VSTs where the target was defined by three dimensions, color, size and shape, search was more efficient than two dimensional searches. This is not predicted by FIT since on average serial search should still terminate after half of the items on a target-present trial and all items on target-absent trials have been inspected. This lead to the *Guided Search* model (GS; Wolfe, Cave and Franzel, 1989, for the latest revision see Wolfe, 2007). Like FIT the GS-model assumes two stages of processing, a parallel stage and a serial stage. Unlike FIT it assumes that serial search is guided by the information obtained during the initial parallel stage. According to the GS model the output from the parallel stage of processing activates dimension-specific feature maps. The collective output of these maps constitutes an activation map, a multidimensional summary of information in a visual scene. This information can then be used to rapidly reject large chunks of the search array and guide the serial process to the locations in the scene, which are most likely to host the target (figure 2). Here GS has a major

---

[1] Author's note

11

advantage over FIT because it explains why the target absent vs. target present tasks do not always return 2:1 slope ratios.

From the looks of the simplified version of feature- and activation maps in figure 2 it would seem that conjunction search should be a very easy task. Just summarize the data from your feature maps and the unique target has been singled out. But this is not the case, as we know from our searching experience.
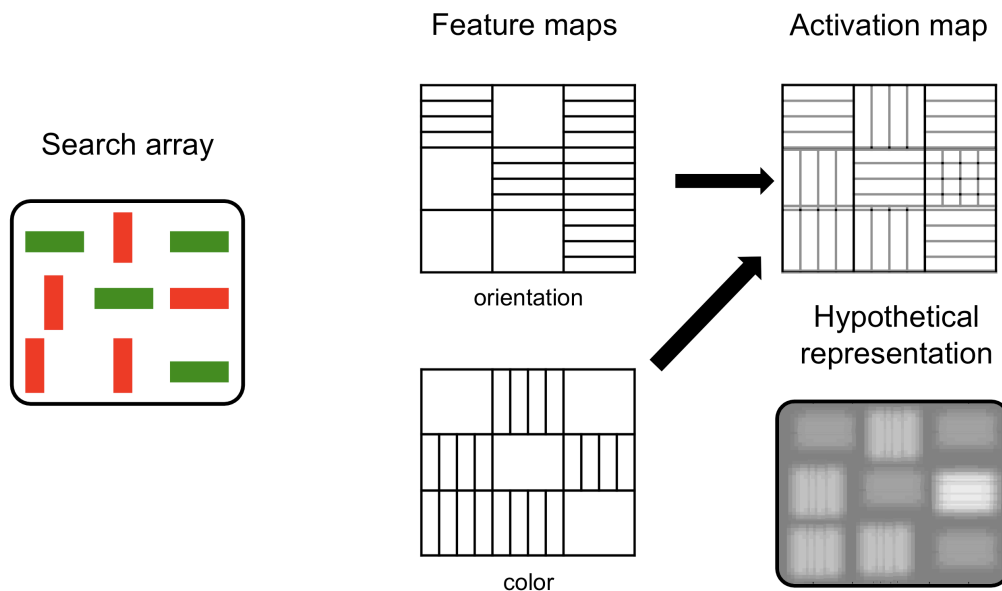

Figure 2. A simple demonstration of the mechanisms that guide search. A search array is presented. A parallel processing stage extracts features in the display into dimension-specific feature maps. The feature maps do not distinguish a unique stimulus in the display. However, if we superimpose one feature map onto another we get a unique square in the 3 by 3 matrix. The overlaid feature maps represent an activity map and within that map the most active location would be the unique square representing the target. The gray-scale image shows a hypothetical representation of the stimuli in the visual system where brightness.

The key word here is *guidance*. GS only assumes guidance from the activation map, not an algorithm for quickly detecting targets. Some features are much more salient than others which will result in strength differences from each feature map. In the example above color signals are much stronger than orientation signals so they will probably be given more weight in the activation map. We must also assume that the guidance of features is limited by the resolution of feature maps. The hypothetical representation map (figure 2) shows how the visual system might represent the information obtained from the search array. In this particular example colors are given twice the weight of orientation. Therefore the green bars in the array are easy to reject, but the red horizontal bars are only slightly darker than the target because orientation is a much less salient feature.

The first version of the GS theory (Wolfe *et al*., 1989) assumed two stages, an initial parallel stage followed by a serial stage. This idea has been abandoned in later versions of the theory. In the newest version (Wolfe, 2007) parallel processing continuously feeds information to the serial processing mechanism, updating information in accordance with new information obtained during search.

The Guided search theory has been revised several times (Wolfe, 1994; Wolfe and Gancarz, 1996; Wolfe, 2007) to account for several phenomena in VSTs. Some of these revisions have addressed the role of memory in visual search.

1.2 The role of memory in visual search

The concept of memory is a controversial one in visual search. Although the more recent versions of GS do take some well established memory effects into account, its author has found it difficult to accept any such role as the title of one of his papers "Visual search has no memory" (Horowitz and Wolfe, 1998) suggests. The controversy has focused mainly the *Inhibition of return*, an effect commonly observed in certain visual search tasks where revisitation of a recently inspected item is inhibited (less likely to occur) and, when forced, slow compared to other items (Klein, 2000). In the context of modeling behavior in search the controversy comes down to whether items in a search array are sampled with or without replacement. Horowitz and Wolfe (1998) presented subjects with dynamic VSTs where under one condition the items (L's among T's) remained in the same location during a trial but rotated every 110 ms. In the other condition items were also relocated every 110 ms. The search slopes under both conditions were similarly steep and the authors concluded that location memory did not play a role in visual search. However, with some critical changes to the parameters of their experimental design, Kristjánsson (2000) failed to reproduce these results and found very compelling evidence of location specific memory.

Many authors have challenged the *amnesic* view of visual search. An inspection of eye-movements during search in a reproduction of Horowits' and Wolfe's (1998) dynamic search task showed that re-visitations were less frequent and more systematic than the amnesic version of GS would predict (Peterson, Kramer, Wang, Irwin and McCarley, 2001). The most vocal proponent of inhibition of return, Raymond Klein, originally proposed that during search the visual system "tags" locations of rejected items (*inhibitory tagging*; Klein, 1988) but other researchers failed to replicate results supporting with this explanation (Wolfe and Pokorny, 1990). While there is ample evidence for some kind of inhibitory mechanism in search, the explanation has to be more complex. For example search slopes get steeper for rapidly moving stimuli in dynamic visual search but not in slow moving or static displays (Wang, Zhang and Klein, 2010; Hulleman, 2009). This is clearly inconsistent with inhibitory tagging of certain visited locations since movement at any reasonable velocity would work against location-specific tagging. Object-centered inhibitory tagging could explain some of the results. Such a mechanism would be able to follow slow moving objects better than fast moving objects. It would also be more effective for small rather than large search arrays due to limited memory capacity.

In the spirit of compromise the GS reserves a small role for memory in visual search. In the model every inspected item is inhibited for a few frames of sampling. The inhibition is lost from memory according to a probabilistic rule leaving an average of 3 items in memory at any time during search (Wolfe, 2007).

Finally, the first author of GS recognizes that his theory is wrong in many ways (just like all competing theories of visual search; Wolfe, 1998, pp. 38). However, it is under constant revision and remains the most influential theory of visual search.

1.3 Repetition priming in visual search

The topic of the current thesis is a different kind of memory in visual search: repetition priming (or inter-trial priming). Repetition priming is an effect manifested by faster responses and/or increasing accuracy when a target or distractor is repeated on a subsequent trial. In fact, the repetition of a single feature of a target/distractor can induce priming effects during visual search. These inter-trial effects are not yet accounted for in the GS despite the author's recognition the phenomenon and intentions to account for it in a later revision (Wolfe, 2007).

In the early 90's priming effects became a subject of rigorous study, mainly by Ken Nakayama and colleagues (Bravo and Nakayama, 1992; Maljkovic and Nakayama, 1994) but also by others (e.g. Treisman, 1992). At the time, models of visual search were often heavily reliant on the subjects' top-down knowledge of the target identity. In most VSTs subjects were asked to search for a particular stimulus, e.g. a red circle. But search for an odd-one-out target does not require foreknowledge of the target features, only a comparison of a target to distractors. Bravo and Nakayama (1992) reasoned that this kind of search could not rely heavily on top-down information and therefore the stimulus characteristics would have a larger role in guiding attention. They experimented with a simple feature search design (with stimuli similar to figure 1C). Their results showed that RTs in an experiment where the target had a consistent identity were faster than when target identity was random. This effect was very large when there were few distractors in the display but shrank with increasing distractors up to set-size about 8-10. For set-sizes larger than 10 the random condition RTs as functions of set-size become approximately parallel to those of the consistent condition and slopes are of negligible size (figure 3).
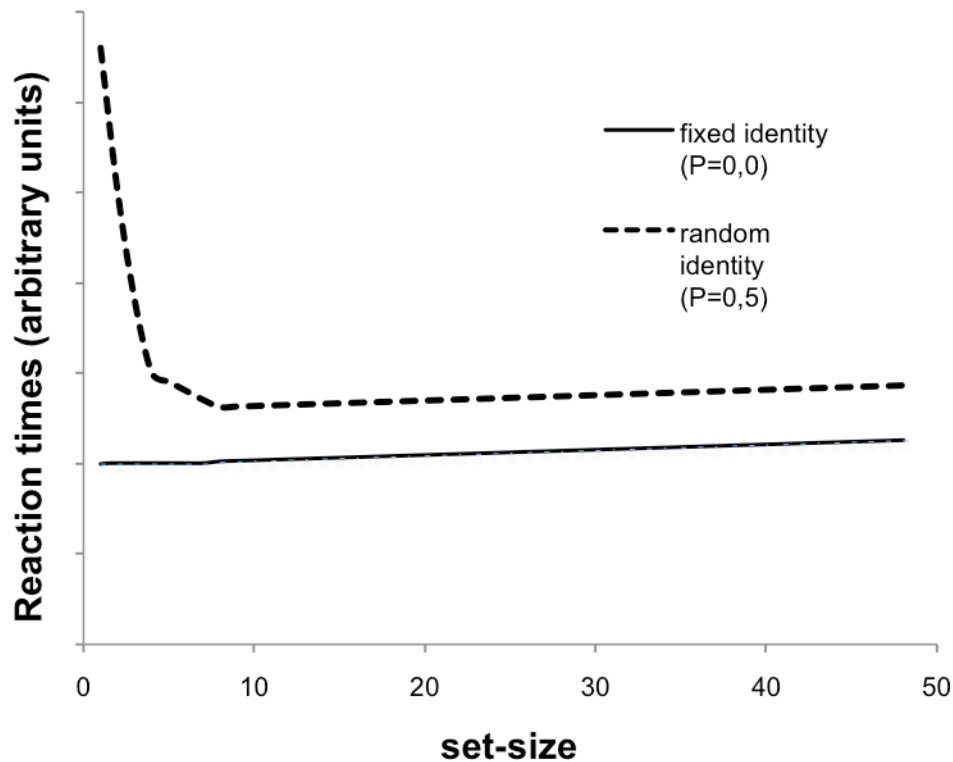
Figure 3. Imaginary reaction times as a function of set-size and probability of change in target identity (Based on the results of Bravo and Nakayama, 1992).

In figure 3 I have plotted imaginary reaction times similar to those found in the paper by Bravo and Nakayama (1992). It has been mentioned before that very small set-sizes can return steep negative slopes. This is only observed in search tasks where stimulus identity is variable between trials, presumably because the subject must resolve the ambiguity of target identity. The ambiguity is at a maximum when the target is presented with only two distractors (the minimum number for this type of search) but decreases when the subject is given more evidence of which color/shape/etc. defines the target from the distractors. When the set-size has reached some quantity *n*, the slopes become positive again, but only slightly in the case of efficient (pop-out) feature search.

For our discussion the most important features of the slopes in figure 3 are the different intercepts. One interpretation of the different intercepts is that stimulus guidance is not as effective as top-down guidance in the particular tasks presented by Bravo and Nakayama (1992).

In later studies with similar stimuli Maljkovic and Nakayama (1994) proposed another interpretation of the difference between stimulus vs. top-down guidance differences in reaction times. Their focus was on repetition priming, a facilitation effect seen when a target remains the same on two or more consecutive trials. Their paper was the first rigorous exploration of repetition priming in visual search and in it they showed that the gap between the aforementioned intercepts could be explained, (at least in part) by repetition priming.

A critical point from the Maljkovic and Nakayama (1994) study was that if the different intercepts are really due to top-down guidance then the target identity need not be fixed, only perfectly

predictable. So whether an experiment has a fixed target identity or a target that predictably changes identity on every trial should return similar reaction times and slopes. To test this hypothesis they replicated the experiments of Bravo and Nakayama (1992) but manipulated the probability of target identity change. The top-down hypothesis would predict the results to be arch-shaped where the lowest mean reaction times are seen when the target identity is maximally predictable (never changes or changes every trial) but gradually increasing towards p=0,5 from both ends of the spectrum. Their favored hypothesis, that the different intercepts were produced by priming effects predicted a monotonic increase in reaction times from p=0,0 to 1,0. Although neither hypothesis was confirmed (the rise in RTs was not strictly monotonic) the results were certainly not in accordance with a strong theory of top-down guidance. The slowest RTs were seen in the fully predictable p=1,0 condition while the fastest responses were seen in the other fully predictable condition when the target never changed identity (Maljkovic and Nakayama, 1994). The results are difficult to interpret in terms of strong top-down guidance without an ad-hoc addition of a large switch-cost during change in target color. However, such an addition would greatly diminish the effectiveness of a top-down guidance system. A system that has such difficulty in changing the target identity representation would not work very well in visual search. A more plausible interpretation is that the repetition of the target (or a salient target feature such as color) is more readily processed by the visual system when it is presented two (or more) times in a row. This facilitation in item processing will then account for some or, perhaps, all of the difference in intercepts seen in figure 3.

Similar differences in intercepts were found by Kristjánsson, Wang and Nakayama (2002) in a conjunction search task. The stimuli were red and green bars oriented horizontally or vertically. The most important manipulation was the probability of change in target identity, from a vertical to a horizontal bar. Four experimental conditions were tested: (1) a random condition were the target changed identity with a 0,5 probability, (2) a switch condition were the target changed identity on every trial (p=1,0), (3) a streak condition where the probability of repetitions was increased beyond what would be expected by chance, but nonetheless not predictable and (4) a condition where the target identity was fixed throughout (p=0,0). As predicted by GS and reported by Bravo and Nakayama (1992) in a pop-out VST the fixed target condition returned the fastest RTs. Contrary to the predictions of the GS theory, the switch condition was the slowest despite full predictability of target identity. The random and streak conditions returned very similar reaction times in between the fixed and switch conditions. The search slopes were very similar under all conditions, which leave us without an explanation of the difference in intercepts just like in the Bravo and Nakayama studies (1992). Kristjánsson *et al.* (2002) went on to analyze the data from streak condition by number of repetitions. This analysis showed that when target identity was constant for 6-8 repetitions the intercept did not differ from the fixed identity intercept. So in this particular task repetition priming could account for all of the effects previously attributed to top-down guidance. Subsequent studies have repeatedly shown that priming can yield significantly faster responses than knowledge of target identities. The mechanism of priming is also presumed to be in use during other types of rapid learning, e.g. learning of a cue-target relationship in cued visual search tasks (Kristjánsson, 2006a).

Now that I have shown that priming has large implications for current models of visual search I will give a short introduction to the general findings on priming and the theories to explain those findings.

1.4 Priming - Common attributes

As mentioned before, Maljkovic and Nakayama (1994) published the first rigorous studies of priming effects. Their collaboration on a trilogy of papers, Priming of pop-out I-III (Maljkovic and Nakayama, 1994; 1996; 2000) describes many of the most important attributes of priming.

In multiple experiments they showed that repetition of color, shape and orientation facilitated responses in pop-out visual search tasks. They showed that the effect of repetition would accumulate across 5-8 trials where it would reach its maximum, that repetition priming was both a facilitation of target features and inhibition of distractors and that only task-relevant features were primed, not the irrelevant features (Maljkovic and Nakayama, 1994). This last effect has been shown to be conditional on search task parameters (e.g. Kristjánsson, 2006a).

In their 1996 paper they focused on priming of position. These experiments showed that priming could occur for previous target positions. The effect was cumulative over 5-8 trials (as in feature priming) and positions adjacent to the target were also (but to a lesser extent) primed on the next trial. The experiments also revealed inhibitory effects on distractor positions and that these effects were under all conditions smaller than facilitatory effects of target repetition (Maljkovic and Nakayama, 1996).

Maljkovic and Nakayama reasoned that priming was an effect produced by a short-term learning mechanism beneficial for deployment of attention. The mechanism was not related to explicit memory since subjects had no memory of the variable values (e.g. green, vertical, etc.) for more than one trial back (Maljkovic and Nakayama, 2000). The memory traces in the hypothesized system would cumulate and decay rapidly (in 30+ sec). Following these publications the learning mechanism was explored in more depth. In Kristjánsson (2006a) the limitations of the mechanism is described in great detail. It cannot learn simple rules such as *if* x *then* y but seems to be entirely reliant on recent associations. It cannot be overridden by top-down knowledge of tasks even when participants are carefully informed about task contingencies and encouraged to use the information to their advantage.

An important attribute of the priming effects described by Maljkovic and Nakayama (1996) is that the effects of one dimension are presumed to be independent of another. So priming of position should occur when position is repeated even if the color of the target is changed and vice versa if position is changed but not color. This means that the mechanism uses primitive information such as rough features (e.g. red or square) and position rather than holistic representations (e.g. red triangle in the upper right corner of the array). This fits quite well into the GS if we assume that repetition affects the processing in the hypothesized feature maps, which are presumed to be independent of each other. Some authors have argued against this mechanism of priming and presented results where priming seems to be object-based or holistic rather than independent and additive (Huang, Holcombe and Pashler, 2004; Hillstrom, 2000). It seems that both sides of this argument have valid contributions

to the priming literature but a question remains: What conditions produce independent feature priming vs. episodic priming? This will be the topic of the remainder of the thesis.

2   Priming in visual search - Episodic retrieval or feature facilitation?

Prominent theories of visual attention and visual search state that items that stand out against the distractor items in the visual search array on a particular feature such as color, shape or orientation, will effortlessly "pop-out" from among the distractors (Julesz, 1984; Treisman and Gelade, 1980; Wolfe *et al*., 1989). An important qualification to this was, however, provided by the findings of Maljkovic and Nakayama (1994) who found that even such highly salient target items were found more quickly (and also found more accurately; see e.g. Sigurdardottir, Kristjánsson and Driver, 2008) if the same target was repeated from one trial to the next compared to when the target identity changed. Such search was thus shown not to be as "effortless" as previously implied.

Such repetition priming in visual search tasks has attracted a lot of interest in recent years, since the pioneering studies of Maljkovic and Nakayama, (1994, 1996). Priming of this sort has been shown to have a surprisingly large effect upon response times in various types of visual search tasks (Hillstrom, 2000; Geyer, Müller and Krummenacher, 2006; Lamy, Bar-Anan and Egeth, 2008; Olivers and Meeter, 2006) and can, in some cases, account for effects attributed to top-down guidance in many theories of visual search (see e.g. Becker, 2008; Kristjánsson, Wang and Nakayama, 2002; Wang, Kristjánsson and Nakayama, 2005; Wolfe *et al*., 2003).

This importance of priming for visual behavior makes it all the more important to understand its characteristics, the mechanisms responsible for it and so on. Two accounts for why these priming effects occur have been most prominent: Feature facilitation accounts (Becker, 2008a, 2008b; Kristjánsson, 2006a, 2008; Maljkovic and Nakayama, 1994; Nakayama, Maljkovic and Kristjánsson, 2004) and episodic retrieval accounts (Hillstrom, 2000, Huang, Holcombe and Pashler, 2004; Huang and Pashler, 2005). Maljkovic and Nakayama (1994) tested performance on a single feature visual search task where the observers had to indicate whether there was a notch at the right or left of a target diamond (either red or green) among distractors of the other color, finding that repetition of the color of the target speeded the search, compared to when the target color changed. Maljkovic and Nakayama proposed that this reflected facilitation of attention shifts, essentially determining what features we will be most likely to attend to following the search. As red is repeated, our attention is drawn to red items in the visual field and the distractor color (green) is inhibited (see e.g. Becker and Horstmann, 2009; Goolsby and Suzuki, 2001; Sigurdardottir *et al*., 2008 for related accounts and Kristjánsson, 2006a, Kristjánsson and Campana, 2010 for review).

An important challenge was, however, made to this view in experiments reported by Huang, Holcombe and Pashler (2004). In their singleton search task, observers searched for an odd-sized target among distractors (target and distractors were either black or white, determined randomly) and reported its orientation. If the target was small on the current trial the distractors were large and vice versa. The critical finding was that when the same sized target was repeated as on the last trial,

search was faster if the target had the same brightness as on the last trial but when the target size was different than on the last trial, repetition of the target brightness actually *harmed* performance. Priming from repetition of size was thus not independent of whether the targets' brightness was repeated or not.

From these results Huang *et al.* (2004) argued that the most parsimonious account for these results was that priming reflects facilitated processing of whole objects rather than single features, in particular an episodic memory representation of the previous trial, which then influences response selection following the identification of the target. This means that the priming exerted its effects at a relatively late stage of the perceptual process. Hillstrom (2000), argued for a related account of priming, proposing that priming does not affect the saliency of repeated features but reflects later episodic memory traces of the foregoing trial. This result was seemingly at odds with what Maljkovic and Nakayama claimed, that the attended *feature* was selectively facilitated (see also Nakayama, Maljkovic and Kristjánsson, 2004; Kristjánsson, 2008), most likely reflecting facilitation at earlier levels of processing than what was proposed by Huang *et al.*

2.1 The current aims

The main purpose with the current experiments was to test the generalizability of the findings of Huang *et al*. (2004) and to test the explanatory power of the episodic retrieval account in terms of priming effects in pop-out visual search. Since the findings have important implications for theories of visual search and priming in particular and visual attention more generally, it is important to replicate the critical findings and to extend them to other search situations.

Our first experiment is more or less an exact replication of the critical experiment reported by Huang *et al*. (2004). In the experiments that follow we test whether the critical interaction found by Huang *et al*. generalizes to other singleton search task, and also deal with some potential confounds in their original studies, which may have biased the interpretation of their findings. We also test whether the results can be generalized to a chromatic version of the same task. This is potentially important since many have found large differences in performance between luminance contrast search versus color contrast search (Theeuwes and Kooi, 1994; Wang *et al*., 2005).

The second and third experiments were designed to address the question of whether between-trial role reversals of target and distractors in Huang *et al*. (2004) and the current experiment 1, had a confounding effect on the critical findings of an interaction between repetition of size and brightness. The role of each target size was reversed when target size changed from one trial to the next. Such role reversals can have notable effects in visual search tasks, effects that can be dissociated from target repetition and distractor set repetition effects (Kristjánsson and Driver, 2008). Furthermore, the potential effects of repetition of distractor sets were not taken account of in the studies of Huang *et al.* (2004) since as the size of the target was repeated, so was the size of the distractors. Such repetition of distractor sets has been seen to have dramatic effects upon search performance (Geyer *et al*., 2006; Kristjánsson and Driver, 2008; Lamy *et al*., 2008) in some cases even stronger than effects of repeating target properties (Geyer *et al*., 2006).

The second experiment was aimed at testing the generalizability of the Huang *et al.* finding of an interaction between repetition of shape and brightness with a different stimulus set and a task involving judgments of the presence or absence of the target. In both experiments (2b and 2b) we used the same target stimuli but in 2b we changed the distractors to a different shape. Experiment 2b was conducted to ensure that we were indeed testing a pop-out visual search task and experiment 2b was performed to avoid the potential confound of between-trial role-reversals between targets and distractors in experiment 2a.

In the third experiment we use targets and distractors similar to Huang *et al.* (2004) with one important difference: the distractors have a fixed size on every trial while the targets vary between being bars smaller or larger than the target to control for effects of distractor repetition and role-reversals.

In all three experiments we varied the set-size between trials in order to test whether the task did indeed involve efficient pop-out search, which the episodic retrieval account is intended to explain.

In experiment 4 we test whether the low size contrast (defining dimension) relative to brightness contrast (irrelevant dimension) has a causal role in the critical episodic interaction observed by Huang *et al.* (2004).

This issue of set-size will be discussed in a special section on page 22, where the implications of the observed set-size effects for theoretical accounts of priming are discussed.

2.2 Experiments 1a & 1b – Replication of the critical experiment of Huang *et al*. (2004).

2.2.1 Methods

Participants. Eight students at the University of Iceland participated in the experiment. All subjects reported normal or corrected-to-normal vision. Seven subjects were unaware of the purpose of the experiment. The 8th subject was the first author (ÁGÁ).

Stimuli and apparatus. A 400 MHz Macintosh computer was used to generate the stimuli, which were presented on a 14" 65-Hz CRT monitor. The same computer was used to collect responses by key-press. An area of approximately 24 by 24 degrees of visual angle on the screen constituted the search array. Viewing distance was approximately 40 cm. The Vision Shell® toolbox (Comtois, 2003) for C was used to program the stimuli and to collect responses.

The search array contained 16, 32 or 48 items on any given trial (see figure 4A). The target, a bar oriented +/-45° from a vertical position, was present on every trial. The observers responded whether the odd-sized bar was oriented to the left or right (orientation varied randomly between trials). The target varied randomly between two sizes (defining variable), 1° or 1.6° long, 0.4° wide and varied randomly in brightness (black or white). The distractors were always of the opposite size but like the target, their brightness and orientation varied randomly. The target was thus either 1° long among distractors 1.6° in length, or vice versa, so if the target identity changed between trials the target identity became the distractor identity. The search items in experiment 1a were either black (<1 cdm^{-2}) or white (80 cdm^{-2}) presented on an approximately mid-grey (22 cdm^{-2}) background. In experiment 1b

the search items were either green (29 cdm^{-2}) or red (22 cdm^{-2}) on the same grey mid-grey background.

Procedure and Design. Before data collection started the observers were told to respond as quickly and accurately as possible to the orientation of the singleton target (of different size than the rest of the items on the screen) and were shown example stimulus displays. They then completed a practice block of 30 trials to familiarize themselves with the task. Responses were made with the index and ring fingers of the participant's right hand by pressing the keys 4 (-45° tilt) or 6 (+45°tilt) on the keyboard number pad. A high-pitched tone designated the start of a trial; a medium pitched tone was given as feedback upon a correct response and a low-pitched tone when the response was incorrect. Data from incorrect responses and reaction times +/- 3 standard deviations from the observers mean reaction times were discarded before data analysis. Each observer participated in a total of 300 experimental trials completed in one block.

2.2.2 Results and Discussion

Experiment 1a

In this first experiment we replicated experiment 1 in Huang *et al*. (2004, exp 1) with one exception. Instead of presenting a fixed number of items in the search display, we varied the set-size between 16, 32 and 48 items (determined randomly for each trial). We also tested subjects on a chromatic version of the same task (exp. 1b).

The response times as a function of whether the size of the target, its brightness, or both brightness and size changed or not is shown in figure 4B. A 2 by 2 repeated measures ANOVA with the factors size repetition and brightness repetition revealed a size repetition main effect of 126 ms. (F(1, 7)=11,437; p=0,012) but the main effect of brightness repetition was only marginally significant (p=0,063). As in Huang *et al.* (2004, experiment 1) there was a significant interaction between size repetition and brightness repetition (F(1, 7)=8,466; p=0,023) accounting for the -2 ms. priming effects of brightness repetition when size alternated but a positive priming effect of 90 ms. when size and brightness were both repeated (figure 4B). These results are in basic agreement with the results of experiment 1 in Huang *et al*. (2004) and support the claim that repetition of both target features is necessary for repetition facilitation effects to be seen.

We also performed a *set-size*size rep.*brightness rep.* ANOVA to explore possible effects of set-size on reaction times. This analysis revealed similar main effects of both size and brightness repetitions and an interaction effect between the aforementioned variables. However, this analysis also revealed a highly significant main effect of set-size (F(2, 14)=26,449; p<0.001) accounting for the considerable difference in reaction times between set-sizes. This difference was 169 ms. between the 16 and 32 item search arrays and 279 ms. between the 16 and 48 item arrays (see figure 5). This clearly shows that this particular task is not a "pop-out" visual search task. This is crucial for determining the validity of an episodic retrieval account of priming of pop-out. (This subject will be discussed in more depth in the section *Effortless pop-out search or difficult serial search? The effects of set-size*).

Table 1 shows the error rates from all five experiments. A 2 by 2 repeated measures ANOVA did not reveal any effects of feature repetition on error rates in experiment 1. This shows that there was no speed-accuracy trade-off as either of the features was repeated.
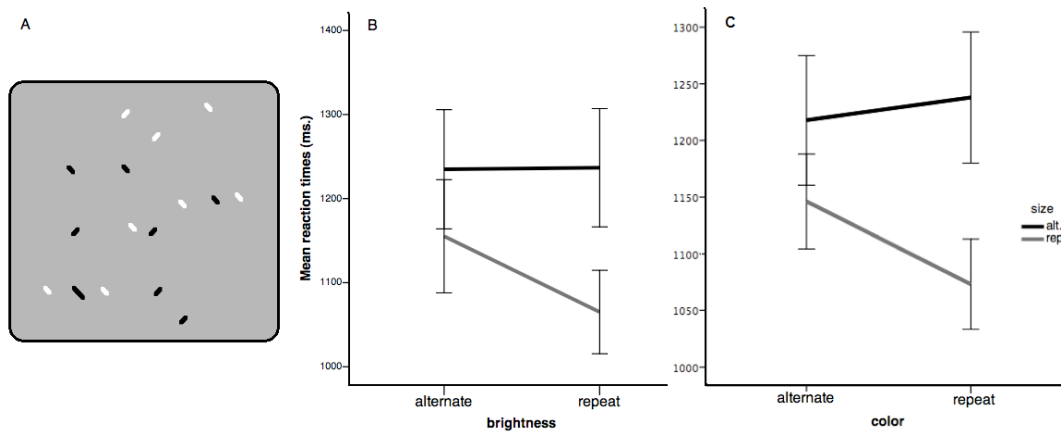
Figure 4. A: A typical search array from experiment 1 showing a large black target amongst 15 smaller black and white distractors. B and C: Mean reaction times from experiments 1a and 1b by alternations and repetitions of the features *brightness* and *size.* Error bars represent ± 1 SEM.

Table 1. Error rates from all 5 experiments as a function of condition.

	Both change		Size/shape repeated[a]		Color repeated		Both repeated	
Exp.	Mean %	SEM	Mean %	SEM	Mean %	SEM	Mean %	SEM
1a	3,7	1,2	3,5	1,0	2,8	0,5	2,3	1,0
1b	2,0	0,6	2,6	0,6	3,2	0,8	2,4	0,6
2a	2,6	0,7	1,5	0,5	1,8	0,5	2,1	0,7
2b	6,4	0,9	3,3	1,4	7,4	1,1	3,2	0,9
3	4,8	0,9	2,5	0,4	1,9	0,8	2,0	1,0
4	3,2	1,4	3,8	1,0	3,3	1,0	2,1	1,0
5	3,0	0,5	2,9	1,0	3,0	0,8	2,4	0,7

a. The target defining variable is *size* in exps. 1, 2 and 3 and *shape* in exps. 4 and 5.

Experiment 1b

The results from experiment 2 are shown in figure 4C. A repeated measures ANOVA revealed a 118 ms. priming effect of target size repetition ($F(1, 7)=15,788$; $p=0,005$) but not of color repetition (39 ms.; $F(1,7)=1,923$; $p=0,208$). The interaction between the repetitions of the two variables was not significant ($F(1,7)=3,816$; $p=0,092$), although the trend clearly indicates such an interaction. Figure 4C

shows a trend towards similar results as were reported by Huang *et al*. (2004), a negative effect of color repetition without size repetition (-20 ms.).

A further *set-size*size rep.*color rep* repeated measures ANOVA confirmed the main effects of the first 2x2 analysis but the interaction effect between repetition of size and color was still not significant. This ANOVA also revealed a main effect of set-size (F(2, 14)=28,232; p<0.001) accounting for 195 and 316 ms response time differences between the small and medium and small and large set-sizes (see figure 5 in the section on set-size effects on pages 22-23). This reaction time pattern is very similar to that found in experiment 1. As in experiment 1, this shows that the search task is in fact not a pop-out task. No interactions were found between set-size and feature repetitions. A 2x2 repeated measures ANOVA on the error rates did not reveal any significant effects of feature repetition, showing that there was no speed-accuracy trade-off as a function of the different conditions in experiment 2 (see table 1).

The first two experiments show that the basic findings of Huang *et al.* (2004) are replicable and generalizable to a chromatic stimulus set. However, we need to address the set-size effects and their implications for the comparisons made by Huang *et al.*

2.3 Effortless pop-out search or difficult serial search? the effects of set-size.

A potentially important variable not addressed in the experiments of Huang *et al.* (2004) are the effects of set-size, the number of items on screen at any given trial. Huang *et al.* kept set-size constant (at 20 items) while we used three different set-sizes, 16, 32 or 48 items. The fact that Huang *et al*. kept set-size constant in their experiments is somewhat unfortunate since their account was aimed at explaining pop-out search, and the easiest way to determine that a particular search is indeed a pop-out task where the target is effortlessly distinguished from the distractors, is to investigate whether response times or accuracy are affected by changes in the size of the search set. Note that in Bravo and Nakayama (1992), where the search task used by Maljkovic and Nakayama was introduced, search times actually decreased with increasing set-size, a phenomenon that can be explained by reduction of the ambiguity regarding target identity (Meeter and Olivers, 2006).

In the first two experiments where we used stimuli similar to those of Huang *et al.* (2004), there were highly significant main effects of set-size (figure 5). This clearly shows a qualitative difference between our search tasks (replications of Huang *et al.*) and those used in investigations of "priming of pop-out" (Maljkovic and Nakayama, 1994). The argument of Huang *et al.* was intended to apply to priming of pop-out visual search, as an alternative to the feature facilitation view advocated by Maljkovic and Nakayama (see also Kristjánsson and Campana, 2010) and subsequently the effects of set-size should be none or minimal. The fact that the effects of set size are large undermines comparisons between the results of Maljkovic and Nakayama (1994) and those of Huang *et al.* (2004). The two studies may not address the same type of search process. Inspection of the overall reaction times from the two studies in addition to the set size effects supports this claim (figure 5). Because of these discrepancies we tested the same subjects in another experiment, which we hypothesized would yield search slopes close to zero.
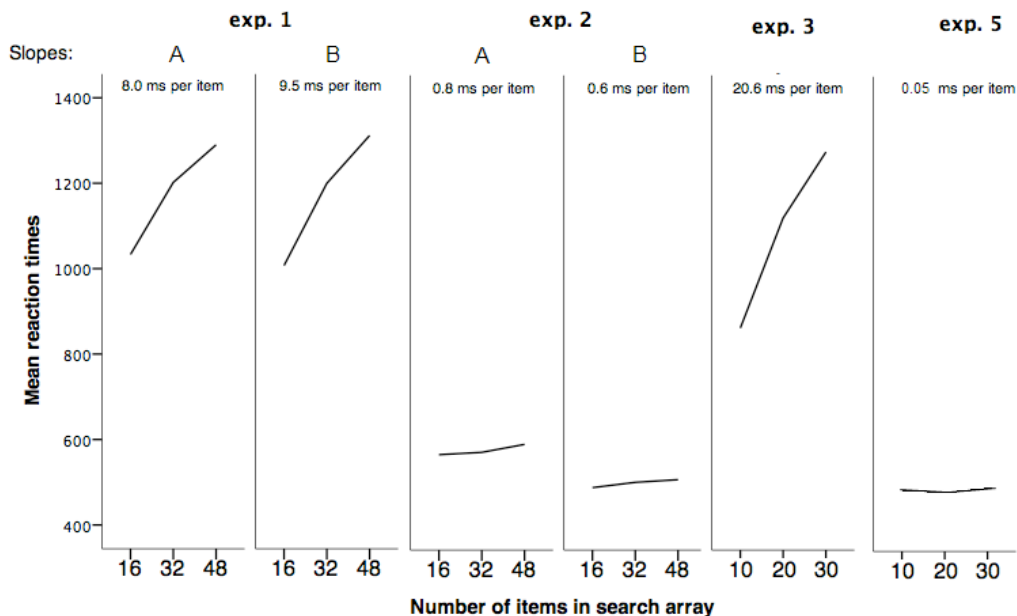
Figure 5. RTs from all experiments as a function of set-size. In the experiments (1 and 3) where search slopes are steep we find an episodic interaction between the reported and irrelevant dimensions. In the experiments where search slopes are negligible no such interactions were found.

2.4 Experiments 2a & 2b - Episodic retrieval versus feature facilitation tested with a different stimulus set

Experiments 1a and 1b showed that the size-singleton, orientation-judgment task used by Huang *et al.* to argue for their episodic retrieval account of pop-out search is not in fact a pop-out visual search task. In experiment 2 we tested the episodic retrieval account using search tasks, which have previously been shown to involve search where the target pops out against the background, but does nevertheless vary in identity on two different features (brightness and shape). We used two distractor sets for this experiment do address the possible confound of target/distractor role-reversals. When a target changes identity from one shape to another in experiment 2a the distractors would take on the previous target identity as well (role-reversals). This was also the case in experiment 1. In experiment 2b the distractors do not share shape with possible targets, which removes competing effects distractor inhibition carried from the previous trial. In experiment 2a shape priming does not compete with distractor shape inhibition.

Despite some differences between tasks in experiment 1 vs. 2 (see *methods*) a strong episodic theory of priming must predict interactions under these conditions as well as those tested previously.

The stimulus sets were chosen because they have previously been shown to be a pop-out search task (Kristjánsson and Driver, 2008; Wang, Kristjánsson and Nakayama, 2005).

2.4.1 Methods

Participants. Participants were the same as in experiments 1a and 1b.

Stimuli and Apparatus. The general set-up and the set sizes were the same as in experiments 1. In both versions (a and b) the target stimuli had two possible shapes (the target defining variable), an annulus (donut) or a disc In experiment a the distractors had the opposing shape (figure 6A). Distractors in experiment b had a different shape, squares or diamonds (figure 6C). The brightness of the targets and distractors was black or white (p=0,5). The diameter of the discs and annuli and the width of squares and diamonds was 11 mm. The apparatus was the same as in previous experiments.

Procedure. The procedure was identical to that described for experiments 1 and 2.

Design. The observers searched for a singleton target defined by its shape. This time the task was a present/absent judgment of an oddly shaped target. The target was now present with a p=0,7 probability on each trial (see Kristjánsson and Driver, 2008). On trials where no target was present, the current and preceding trials were discarded before the analysis since target priming, feature or episodic, could by definition not have occurred.

2.4.2 Results and discussion

Experiment 2a

In experiment 2a we changed the target defining variable from size to shape (discs/annuli, previously used by Wang *et al.*, 2005, and Kristjánsson and Driver, 2008) to explore the generality of an episodic retrieval account of priming of pop-out. If such an account is to be considered a viable candidate for explaining the results of studies of priming in visual search, it must account for such priming results in various paradigms, and similar interaction effects between different features should then be found here as Huang *et al.* (2004) observed.

The results from the target present trials in experiment 4 are shown in figure 6B. A 2x2 repeated-measures ANOVA revealed a main effect of shape repetition priming of 82 ms. ($F(1, 7)=52,211$; $p=0,0002$) but the effect of brightness repetition was not significant ($F(1, 7)=2,970$; $p=0,128$). Most importantly, no hint of an interaction between repetition of shape and brightness was found ($F(1, 7)=0,088$; $p=0,775$) in conflict with the predictions of an episodic retrieval account.
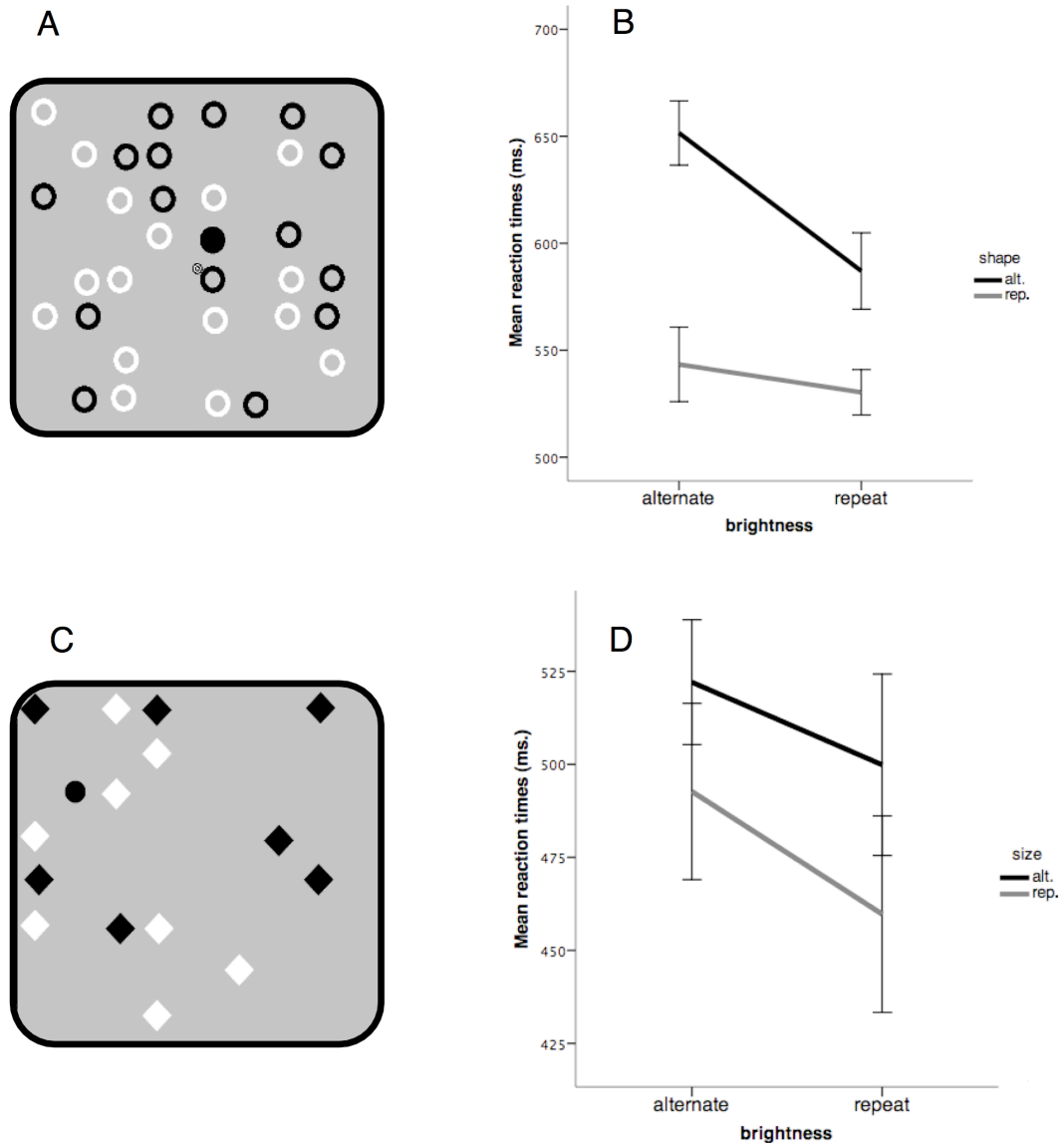
Figure 6. A: A representative search display from experiment 2a. B: Mean reaction times by alternations versus repetitions of the features *brightness* and *shape* from experiment 2a. C: Search display from experiment 2b. D: Mean reaction times from experiment 2b. The error bars represent ± 1 SEM.

A 3x2x2 repeated measures ANOVA with *set-size* added as a factor confirmed the main effect for shape repetition ($F(1, 7)=94,724$; $p<0,001$) and this time also revealed a main effect of brightness repetition ($F(1, 7)=16,783$; $p=0,005$) turning the trend seen in the previous 2x2 ANOVA into a significant effect. The main effect of set-size was marginally significant ($F(2, 14)=3,637$; $p=0.053$) which implies that the search is not fully independent of set-size. The set-size effect is very small however, the slope of set size against reaction times is less than 1 ms per added item to the array, which is dwarfed by the slopes seen for experiments 1 to 3 (see figure 5).

The 3x2x2 analysis also revealed a somewhat peculiar interaction between shape and brightness repetition ($F(1, 7)=6,77$; $p=0,035$). This interaction does, however, not indicate episodic processing as

in experiment 1. Here the priming effects were very pronounced when only brightness was repeated (65 ms.) but very little brightness priming occurred when shape was also repeated (13 ms.). This might reflect that so much priming is carried by shape repetition that little room is left for priming from brightness repetition. Also this interaction suggest that the effect of brightness repetition is stronger when shape is not repeated, a result which is clearly inconsistent with the episodic retrieval account. This interaction argues, in other words, strongly against ER accounts of priming.

The brightness priming effect showed a significant interaction with set-size (F(2, 14)=3,854; p=0,046). When the set-size is small (16 items) the brightness repetition priming effect is similar whether shape is repeated (34 ms.) or not (56 ms.). When the set-size is doubled (32 items) there is a large effect as brightness is repeated but shape alternates (85 ms), but smaller (19 ms) when both features are repeated. Lastly, when searching a 48 item display the priming effects is only seen present when brightness is repeated (52 ms.) but negative when shape is also repeated (-18 ms). As in experiment 3 this may suggest as set-size becomes larger the search strategy changes. A 2x2 repeated measures ANOVA on the error rates did not indicate an effect of feature repetition, which suggests there was no speed-accuracy trade-off (table 1).

According to the episodic retrieval account we should have seen an interaction between the effects of repeating shape and color in experiment A. Instead we find a pattern where considerable priming is seen by repeating either feature, but the largest priming effect is seen when both features are repeated. The episodic retrieval account is clearly not the most parsimonious explanation for the results from experiment A. The results are much better explained by a feature facilitation account where it is assumed that the processing features of the target on the preceding trial (shape and brightness in this case) is facilitated on the next trial and the largest repetition priming effect is seen when both features are repeated, but when only one of the features is repeated search is nevertheless faster than when neither is repeated.

Experiment 2b

The results of experiment 2a showed no episodic interaction between repetitions of the two features on the stimuli that varied between trials (shape and brightness). It is however possible that the fact that the target and distractors reversed their roles between trials may have had an effect upon the results. A typical visual search trial should involve both the facilitation of the target (as a whole or independent features of the target) on the one hand and inhibition of distractors on the other. These effects may interact to return ambiguous effects. Admittedly, if such an interaction was the cause of results such as presented here (experiment 1) and in Huang *et al.* (2004) this would not eliminate the need to explain an active episodic memory mechanism during visual search. It would only move the burden from the mechanism(s) of priming to the mechanism of distractor inhibition.

 In experiment 2b we tested priming performance for stimuli where the potential role-reversal was avoided. We used the same targets as in experiment 2a while the distractors would vary randomly between squares and diamonds (figure 6C). The purpose of this was to remove any possible confound of between-trial role-reversals between targets and distractors which we hypothesize could play a role in creating the interaction between repetition of different features seen in the original results of Huang *et al.* (2004; see experiment 4).

The results from the target present trials in experiment 2b are shown in figure 6D. A repeated-measures ANOVA revealed a 28 ms priming effect ($F(1, 7)=14,37$; $p=0,007$) of shape repetition and a 35 ms. effect ($F(1, 7)=16,036$; $p=0,005$) of color repetition. There was no evidence of an interaction between repetition of shape and brightness on the target ($F(1, 7)=0,393$; $p=0,551$). These main effects were also confirmed by a 3x2x2 repeated measures ANOVA with an added set-size factor. Set-size did not have any effect upon the reaction times ($F(2, 14)=0,528$; $p=0,601$). A 2x2 repeated measures ANOVA on the error rates (see table 1) did not show any effect of feature repetition, which suggests there was no speed-accuracy trade-off in experiment 2b.

Experiment B shows no hint of an interaction between repetition of the two features, shape and brightness. There is instead a strong main effect of the repetition of both features (shape and brightness). The episodic retrieval account, as stated by Huang *et al*. (2004) "locates the priming effect at a decision stage that occurs after a candidate target has been found "(page 20). By that account we should not see independent and additive priming (see also Kristjánsson, 2006b; 2009) for the two features, since the priming effects should occur at levels where the objects are integrated so repeating only one feature should not have a beneficial effect upon such object representations since non-repetitions of the other interferes with identification of the target. The fact that we found significant priming from both features but no interaction shows that the priming is additive - there is considerable facilitation from repeating only one feature, and repetition facilitation is largest when both features are repeated.

While removing the confound of target and distractor interchange returned results compatible with an additive account of priming the role-reversals version of experiment 2 did not return results predicted by an episodic retrieval account. However, we have not yet tested whether this confound was the cause of the critical interaction in experiment 1, which applied a very different stimulus set. We address this question in experiment 3.

2.5 Experiment 3 – Eliminating effects of role reversals between target and distractors

In the critical experiment supporting the episodic retrieval account of Huang *et al.* (2004), the repetition from target characteristics and distractor characteristics was confounded. When the target size changed the distractors took on the size of the distractors on the previous trial and vice versa. It is quite clear that distractor set priming plays a large role in priming in visual search (Kristjánsson *et al*., 2002; Lamy *et al*., 2008; Saevarsson, Jóelsdóttir, Hjaltason and Kristjánsson, 2008) – a role which may be as large as the target priming effects or even larger under some circumstances (Geyer *et al*., 2006). Also, role-reversal between target and distractors can have a strong effect upon search performance, an effect that is independent of the effects of target and distractor priming (Kristjansson and Driver, 2008). In experiment 3 we eliminated this potential confound by keeping the size of the distractors constant while the target size varied between being larger or smaller than the distractors.

2.5.1 Methods

Participants. Eight observers, seven of which were naive, participated in the study. The eighth subject was the first author (ÁGÁ). All observers reported normal or corrected-to-normal vision.

Stimuli and Apparatus. The targets were black or white tilted bars similar to the stimuli used in experiment 1. Their size varied randomly between trials from being larger or smaller than the distractors. The distractors were always of a fixed size (1.9° long) to remove the possible confound of role-reversals between targets and distractors, as explained above. We matched the salience of small and large bars by pilot-testing 5 observers on a number of different target sizes to try to find stimuli where small and large targets would be as equal in salience as possible. These pilot experiments showed that bars of 1° and 3.2° (in length) were the closest approximation to equal salience in that the reaction times for the two sizes were comparable. The set-size range was also changed to include a 20 item search array (for direct comparison with Huang *et al.* (2004)). The set-size in the search array varied randomly between 10, 20 and 30 items (Figure 7A). The apparatus was identical to what has been described for previous experiments.

Procedure and Design. The procedure and design were in most respects identical to those of experiments 1 and 2 (but note the changes in the stimuli; *Stimuli and Apparatus* section). Each observer participated in 500 trials.

2.5.2 Results and discussion

The results of experiment 3 are shown in figure 7B. A 2x2 repeated measures ANOVA revealed a 59 ms main effect of brightness repetition ($F(1, 7)=7,933$; $p=0,026$) and a marginally significant 64 ms effect priming effect from the repetition of size ($F(1, 7)=5,076$; $p=0,059$). Although figure 7B shows a deviation from the additivity of the two features expected under the feature facilitation account there was not evidence to support an interaction between repetitions of the two features ($F(1, 7)=0,829$; $p=0.393$). In fact the pattern looks like an intermediate state between a feature facilitation and episodic retrieval.

A 3x2x2 repeated measures ANOVA, with set-size as the added factor, confirmed a main effect of brightness repetition ($F(1, 7)=16,604$, $p=0,005$) but the size repetition effect was not significant ($F(1, 7)=3,474$, $p=0,105$). This ANOVA also showed a main effect of set-size ($F(1,059, 7,414)[2]=24,637$; $p=0,001$). These differences were 224 ms between 10 and 20 item search arrays and 368 ms between 10 and 30 item arrays. As in experiments 1 and 2 this shows that the task is not a pop-out task despite the increased salience of targets and elimination of role reversals. Importantly no interactions were found in this analysis and most importantly not the critical interaction found by Huang *et al*. (2004), which had suggested that the priming from size and brightness were not independent.

---

[2] Greenhouse-Geisser corrected degrees of freedom due to significant deviations from sphericity.

The results from experiment 3 show that when we eliminated role-reversals between target and distractor identity, the interaction between repetition of size and color is greatly diminished. Experiment 3 indicates that the interaction found by Huang *et al.* and replicated by us in experiment 1 relies at least partly on these role reversals.
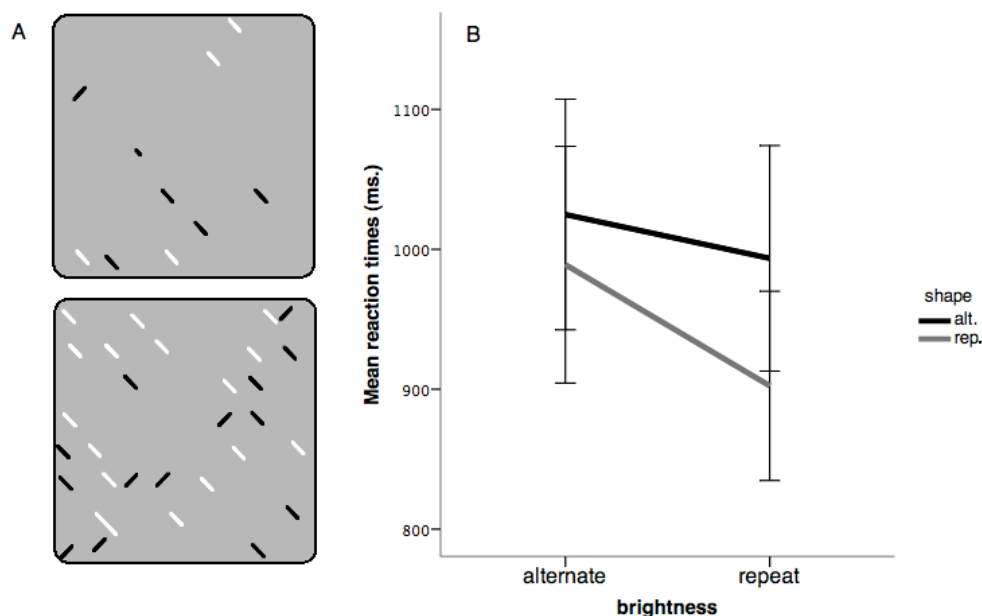
Figure 7. A: Typical search arrays from experiment 3 showing a small black target amongst 9 medium sized distractors (above), and a white large target amongst 29 medium sized distractors (below). B: Mean reaction times as a function of alternations and repetitions of the features *brightness* and *size.* The error bars represent ± 1 SEM.

When the results were split into three groups by set size an interesting pattern emerged. Figure 8 shows that reaction times are relatively fast during search in the 10 item search array and the priming effects for this set size are additive with no hint of an interaction. When set-size was 20, the reaction times slow down considerably, but the pattern still resembles that expected for additive feature priming rather than episodic retrieval (note that this was the set size used by Huang *et al.*, who did not vary the set-size). The priming pattern for the 30 item array was quite different from the pattern seen for the other two set-sizes. Although reaction times are only slightly slower than for the set-size of 20, the pattern is indicative of the critical interaction pattern expected under the episodic memory account of priming. This, most likely, reflects differences in search strategies as the difficulty increases, where subjects may rely increasingly on higher cognitive abilities to process the increasingly difficult search task. We did not have statistical power to confirm these patterns, however, (with the exception of a significant main effect of brightness priming within a 10 item search array; $F=13,475$, $p=0,008$).

It is possible that these results reflect that as the set-size becomes larger, observers may perform a more systematic search than for the smaller set sizes, checking off items or regions already inspected which may not be necessary for the smaller set sizes, and this difference in strategy causes the observed difference in the priming effects.
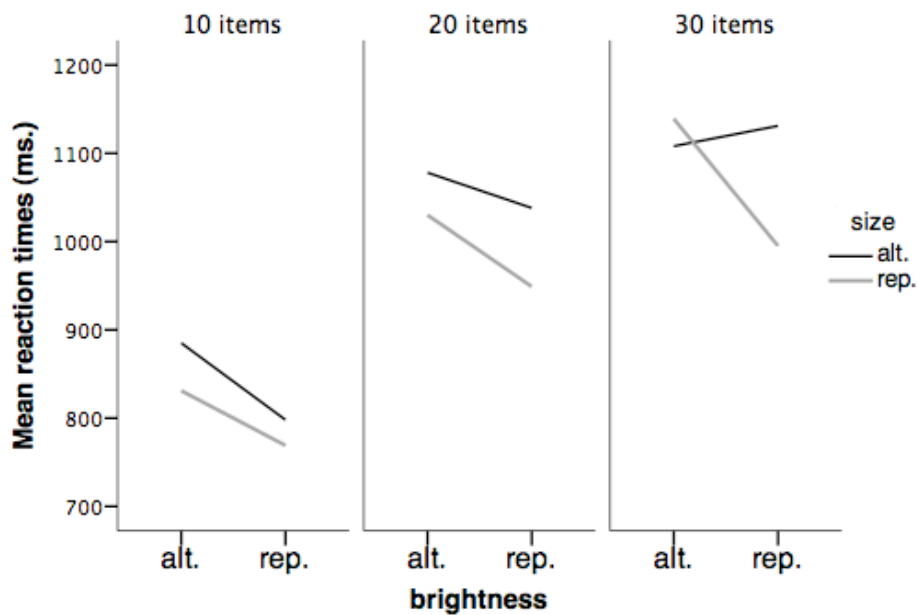
Figure 8. Mean reaction times for the different set-sizes in experiment 3, as a function of brightness repetition and size repetition.

A 2x2 repeated measures ANOVA on the error rates revealed an interaction effect of repeating both brightness and size (F(1, 7)=7,803; p=0,027). Note that this does not indicate a speed-accuracy trade-off biasing the results towards a feature facilitation account of priming, but rather the converse: When one or both features were repeated participants made few errors, while alternating both features increased the error rates (table 1). This suggests that if anything, the response criteria were more liberal when both features were alternated which should reduce rather than enhance priming effects in our results.

The results from experiment 3 raise some important limitations to the explanatory power of the episodic retrieval account. Under the easiest search condition (set size = 10) the priming pattern is best explained under a feature based account (recall that the episodic retrieval account was supposed to explain priming of pop-out in the paradigm used by Maljkovic and Nakayama, 1994, where the set size was 3). There, the priming pattern is additive, where the largest priming effect is seen when both size and orientation are repeated but there is also a large benefit for the search of repeating only one of the target features, as observed by Kristjánsson, 2006b; 2009). A set-size of 20 items shows a condition in between an additive and episodic explanation where repetition of any feature benefits search but repetition of both is superior. Only when the set size was 30 did we see results compatible with an episodic memory account (figure 8).

The results from experiment 3 are also important in that they show (as experiments 1 and 2 before) that the task tested by Huang *et al* (2004) in an attempt at exploring priming of pop-out search is not a pop-out task. Even though it is undoubtedly a single feature search task, the odd-sized target does most certainly not pop-out against the background since there is a large effect of set size which shows

that the target becomes harder to find the larger the number of distractors while pop-out search is defined as search where the reaction times are unchanged with increasing numbers of items in the search array.

Experiments 2b and 3 show that target and distractor role-reversals can change the repetition priming pattern. However, this is obviously not the only causal factor since we still get results better explained by episodic memory accounts of priming when the set-size is relatively large (30 items, exp. 3). In fact task difficulty may also play an important role. As is shown in figure 5 the search slope in experiment 3 is more than twice the size of the slopes in experiment 1. This is most likely because the equally salient target sizes relative to an intermediate fixed distractor size crowds the search array to a greater extent than in experiments 1a and 1b. This is, of course, especially true when the set-size is large, the condition under which the results were compatible with an ER account of priming. This feature of the experimental design may also be the reason for the large standard errors in experiment 3 despite the increase in trials (500 vs. 300 pr. subject).

2.6 Experiment 4 – changing the relative saliency of features in the search array

While we have shown that an episodic retrieval account does not explain priming of pop-out this does not change the fact that Huang *et al*'s (2004) results are an important challenge to a pure feature facilitation account of priming. We have shown that target and distractor role-reversals may exert some effects on priming patterns but have yet to reduce the difficulty of the search to see if there is a clear effect of task difficulty. This flip-side of that same coin is the signal-to-noise ratio in the search array. A difficult search task is difficult because the of noisy surroundings, most commonly produced by similarity between target and distractors, number of distractors or low contrast visual information.

In the previous experiments we have used relatively difficult search tasks. The difficulty is due to the small difference in target vs. distractor size. As shown by the different search slopes the saliency of targets is low among the distractors. However, the stimuli have close to maximal brightness and color contrast since we used black vs. white and green vs. red. This difference in saliency for the reported and irrelevant features may affect how the proposed mechanism of priming processes features in the search array. Therefore we manipulated these contrast differences to make the size difference (defining dimension) more salient among the high-contrast brightness variations of the distractors (irrelevant dimension). We increased the size difference between targets and distractors to counter act the large brightness contrast, without changing brightness. By doing this we increased the signal of the defining dimension and made the task easier to solve. Size was the only difference between this experiment and experiment 1 Huang *et al.* We kept set-size constant to replicate other aspects of their experiment as closely as possible.

2.6.1 Method

Participants. Nine subjects participated in this experiment. Subjects had normal or corrected-to-normal vision. Eight subjects were naïve and one was the author (ÁGÁ). One subject did not complete the A portion of the experiment.

Stimuli and apparatus. The apparatus was identical to exp. 1-3. We used the same brightness contrast as in experiments 1 and 3 (black and white) but increased the size difference between targets and distractors to 1° vs. 2.6°.

The set size in the experiment was fixed at 20 items per trial.

Procedure and design. Procedure and design was identical to experiment 1.

2.6.2 Results and discussion

The results from our previous experiments suggest that search difficulty plays a role in producing the episodic interaction critical for an episodic retrieval account of priming. Here we increased the size difference between targets and distractors to make the search easier while maintaining stimuli similar to those where the interaction was revealed (experiment 1 and Huang *et al.,* 2004).

Mean reaction times ranged from 699 ms. under the no-repetition condition to 657 ms. under the both-repetition condition. As expected increasing the size contrast lowers reaction. A 2 by 2 repeated measures ANOVA revealed a 21 ms. main effects of size repetition (F(1, 8)=33,894; p<0,001) as well as a 21 ms. main effect of brightness repetition (F(1, 8)=11,937; p=0,009). No interaction was seen between repeating the two variables (F(1, 8)=0,18; p=0,682).

While the priming effects are much smaller than in previous experiments their pattern fits a feature facilitation account of priming.

A 2 by 2 repeated measures ANOVA did not reveal repetition effects upon error rates which suggests there was no speed-accuracy trade-off under the different conditions (table 1).

Here we have found yet another way to eliminate the interaction between the defining and irrelevant variables within the experimental design of Huang *et al.* By increasing the signal from the defining variable relative to the irrelevant brightness signals we get approximately additive effects of feature repetition, albeit much smaller effects than in experiment 1.

2.7 Experiment 5 – Changing the defining dimension from size to brightness

Episodic retrieval as a general explanation of priming effects, and particularly priming of pop-out as presented by Huang *et al.* (2004) must generalize over different dimensions. Maljkovic and Nakayama (1994) defined their targets with color in their original studies, while Huang *et al.*(2004) used size. We have hitherto followed the latter in using size to define our targets. We have shown that pop-out search tasks do not reproduce episodic repetition effects. We have also shown that increasing the signal strength of size compared to the irrelevant variable (color or brightness) abolishes the episodic

effect. However, we have not yet put the episodic retrieval account of priming of pop-out to a very important test: Generalization over dimensions.

Here we repeat experiment 1a with an important difference. Now subjects are to report the orientation of a brightness singleton rather than a size singleton.

2.7.1 Methods

Participants. Seven university students participated in the experiment. All of the subjects had some experience with psychophysical experiments. Six were unaware of the hypothesis of the particular experiment while the seventh subject was the first author (ÁGÁ). All subjects reported normal or corrected-to-normal vision.

Stimuli and apparatus. The apparatus was the same as in experiments 1-4. The stimulus parameters, brightness and size, were the same as in experiment 1. Now the targets were defined by brightness (black or white) and therefore all distractors were equiluminant. The irrelevant variable, size, varied randomly for each item in the display. The set-size varied randomly between 10, 20 and 30 items.

Procedure and Design. The procedure and design were in most respects identical to those in experiment 1. The exception was that subjects reported orientations of a brightness singleton rather than a size singleton. All subjects completed 30 practice trial before completing two blocks of 200 trials each (400 total).

2.7.2 Results

A 2 by 2 repeated measures ANOVA revealed a 53 ms. main effect of brightness repetition ($F(1, 6)=120,474$; $p<0,0001$) but size repetition did not yield a significant effect (8 ms.; $p=0,078$). No interaction was seen between the two variables ($F(1,6)=0,228$; $p=0,65$; figure 9).
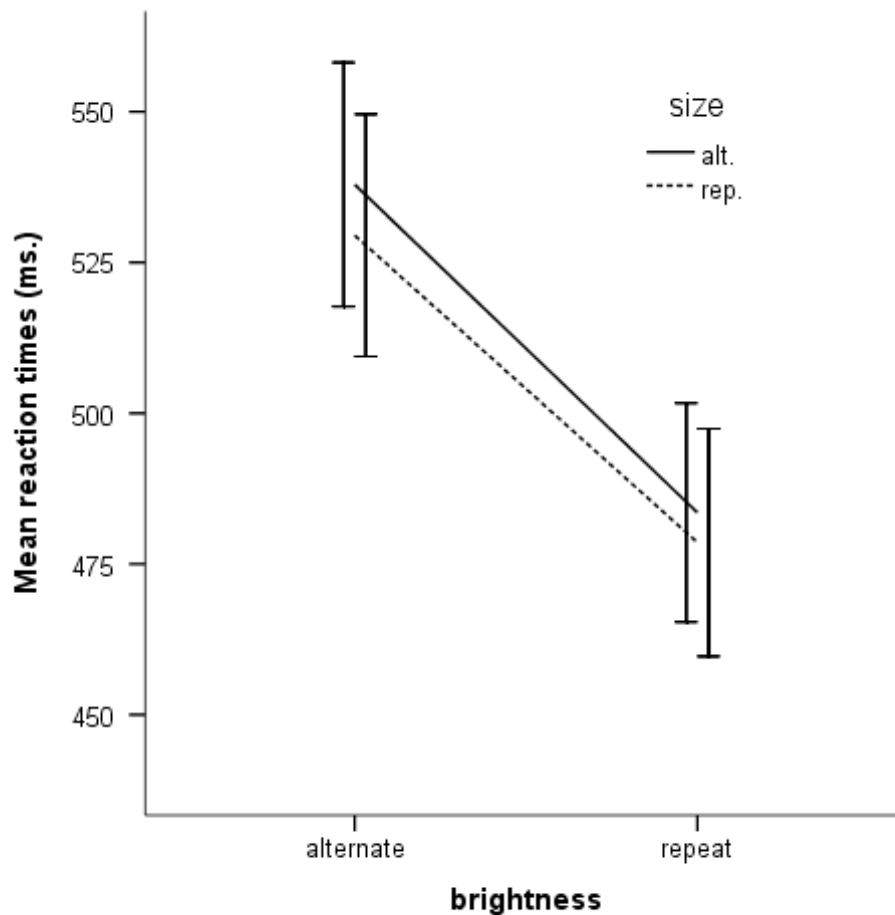
Figure 9. Mean reaction times as a function of repetition and alternations from experiment 5. Error bars represent ±1 SEM.

A 3 by 2 by 2 ANOVA did not reveal any set-size effects (p=0,292) nor interaction effects between set-size and repetition of either feature (p's>0,357).

Analysis with repetition of the response variable (orientation) only confirmed the results of the 2 by 2 analysis. Orientation did not yield main effects (p=0,242) nor did it interact with repetition of size or brightness (F's<1; p's>0,37). In fact the highest p-value was seen for the three-way repetition condition (the truly episodic condition when all features are repeated; p=0,662).

The results from experiment 5 demonstrate the fragility of the episodic retrieval account of priming of pop-out. In fact our result show that there are certainly episodic priming effects but not when the task can truly be called a pop-out task. An episodic retrieval account of priming does not explain any of our data where search slopes are shallow or negligible. This poses a series threat to the explanatory power of any episodic account aimed at explaining priming of pop-out in general. It may however be well suited to explain priming effects under rather specific conditions.

A 2 by 2 ANOVA did not show effects of feature repetition upon error rates (p's>0,38; see error rates in table 1).

2.8 General Discussion

In the eight experiments presented here, we have tested how well the episodic retrieval account of priming of pop-out visual search (see Huang *et al*., 2004; Hillstrom, 2000; see also Huang and Pashler, 2005) can account for a number of different search tasks. We wish to draw the following conclusions from the results of the eight experiments presented here.

1. The original task used by Huang *et al.* is not in fact a pop-out search task even though it is undeniably a singleton search task. Large set-size effects were observed for the task, undermining the claim that the episodic retrieval account is a viable account of the priming of pop-out phenomenon. When tested on approximately zero-slope tasks, observers showed no episodic priming effects.

2. The interaction between repetitions of different features found by Huang *et al.*, (2004) was only seen for very difficult tasks where the defining variable was much less salient than the irrelevant interacting variable. Presumably such a task not only slows down search but also delays decision making since the subject must sample multiple items during a trial rather than be guided straight to the pop-out target.

3. In experiments 2a, 2b and experiment 5 we demonstrate what can be considered true pop-out effects. None of these data show any indication of the critical interaction between defining dimension and irrelevant dimension repetition. This finding implies that episodic retrieval does not explain priming of pop-out. The critical interaction for the episodic retrieval account also does not emerge in smaller set-sizes in experiment 3 (the least efficient task) nor does it emerge in experiment 4 where we did not vary set-size but the reaction times are high compared to the pop-out versions of the task. In experiments 1a and 1b and under the highest (30 items) set-size conditions of experiment 3 we do see the interaction most parsimoniously explained by an episodic retrieval account of priming. The results of the experiments together seem to point, not so much to a pop-out quality of a search task as the necessary attribute for episodic priming to arise, but rather the difficulty or signal-to-noise ratio in the search array. It is plausible to assume that signal-to-noise ratio makes the decision process more difficult by adding uncertainty to the post-perceptual process. In that sense our results may be viewed as supporting a weak version of Huang *et al.*'s claim that priming effects occur at the decisional stage. However, as we have shown that is not the whole story.

4. The interaction between repetitions of different features observed by Huang et al., is certainly problematic for a feature facilitation account of priming. This interaction seems, nevertheless to apply only to a very limited subset of tasks, and may reflect different search strategies than those used in efficient search.

The Huang *et al.*s episodic memory retrieval account of priming locates priming effects at the decision stage of visual processing, later than feature facilitation theories which propose facilitation during selection. A recent paper by Lamy, Yashar and Ruderman (2010) addresses the question of

whether priming is a perceptual or decisional process. Their results argue for a dual-stage account of priming, that what we have hitherto referred to simply as priming are in fact two different phenomena. A dual-stage account of priming may be the most plausible explanation of the discrepancies between the experiments presented here (see also Kristjánsson, Ingvarsdóttir and Teitsdóttir, 2008; Kristjánsson and Campana, 2010). Such an account would include an initial sampling stage where previously sampled features are re-sampled more efficiently than others, and a later decisional stage that benefits from temporarily stored information about previously sampled (whole) items. To fit our data the first stage would be a necessary stage during any visual search task while the later process is recruited under noisy conditions when decision is more difficult. While Lamy *et al.* (2010) do not mention the possibility of overriding the later stage their account of priming with minor modifications fits our data seemingly quite well.

We argue, in other words, that our results favor a feature facilitation account of priming when search is efficient. Such a feature facilitation account seems to be in basic agreement with much of the available evidence (see e.g. Kristjánsson, 2008; Kristjánsson and Campana, 2010).

We do not wish to argue for a one-sided view of priming in visual search. Instead we wish to argue that extreme accounts in either direction are unlikely to reflect the true state of things. There are various reasons for this. Recent neurophysiological evidence, from single–cell studies (Bichot and Schall, 2002), from neuroimaging (Geng *et al*. 2006; Kristjánsson *et al*. 2007) studies of neglect patients (Kristjánsson *et al*., 2005; Saevarsson *et al*., 2008) transcranial magnetic stimulation (Campana *et al*., 2002; 2006) and lesion studies (Walsh *et al*., 2000) indicates that priming reflects activity changes at a number of different neural loci; sites where objects may (at least to a considerable extent) be integrated as well as areas that are involved in the processing of features (such as brightness, color, motion or shape). Priming effects have been found as early as in extrastriate cortex with fMRI (Kristjánsson *et al*., 2007), but also at later stages of perceptual processing.

In addition, behavioral evidence for what might be termed a "hybrid" view of priming comes from the results of Kristjánsson, Ingvarsdóttir and Teitsdóttir (2008), who found evidence which suggests that whether priming patterns in visual search reflect facilitated processing of integrated objects or features depends heavily on the type of stimulus that priming is being tested for. They tested a relatively difficult search task, where observers searched for diamonds that contained two colors (on either side of their vertical midline, or a smaller diamond embedded within a larger one). These two types of stimuli have been shown in visual search studies (Wolfe, Friedman-Hill and Bilsky, 1994; Xu, 2002a) and studies of visual short-term memory (Vogel, Woodman and Luck, 2001; Xu, 2002b, see also Kristjánsson, 2006c) to be processed differently by the visual system. The degree to which particular stimuli tended to be perceived as whole objects or separate features determined strongly whether the effect from an objects' repetition reflected what one might call object-based priming (which would be consistent with the episodic retrieval account) or feature-based priming.

Also, the results of Kristjánsson (2006c; see also Kristjánsson, 2009) where dissociable priming effects from repetition of different features were observed also indicate that priming of whole objects cannot be the whole story. Priming is thus likely to involve facilitation at several levels of the

perceptual process. Perhaps a ''hybrid'' view in which priming is thought to involve facilitated processing at various different processing levels is perhaps the most parsimonious account of the available results (see e.g. Kristjánsson and Campana, 2010). It is however undeniable that most of the results of priming studies available in the literature support feature facilitation, and our current results cast some serious doubts upon the explanatory power of the perhaps most prominent alternative candidate account.

Other results questioning the explanatory power of episodic retrieval accounts comes from the studies of Becker (Becker, 2008a; see also Becker, 2008b for converging results), where the effects of repetition of target features were investigated in a visual search task involving eye movements. Becker found that priming effects clearly modulated the accuracy and time-course of the first saccade in the search sequence within a trial during active visual search (where eye movements are allowed). These initial saccades were faster and more accurate when the same target was repeated than when it changed between trials indicating that priming affects "the attention driving capacity of target and non-target items on a trial-by-trial basis" as Becker (2008a, p. 325) put it. This suggests, in other words, that priming affects search at an early stage of attentional guidance, *before* selection of the first item in the display. Becker and Horstmann (2009) argued, partly based on these results of Becker (2008a), for a "feature weighting" account of priming where priming is assumed to weight feature values similar to the target on the last trial more highly than others, a view broadly consistent with feature facilitation accounts of priming in visual search.

2.9 Conclusions

Our results here indicate that the interaction between repeating different features used to argue for episodic retrieval accounts of priming is seen only when search the saliency of an irrelevant variable is very strong compared to the defining variable. This may reflect a dual-stage process similar to Lamy *et al*.'s (2010) account of priming in visual search or even a multi-stage process as suggested by Kristjánsson and Camapana (2010). Neither of these accounts have been elaborated in great depth. Future research on priming should address the implications of the different multi-stage hypotheses and seek to integrate the various processes that yield priming effects in visual search and other experimental paradigms.

Episodic retrieval does not account for the priming of pop-out phenomenon but has an important, albeit limited, role in theories of visual search. A careful examination and quantification of signal-to-noise ratios in visual search arrays may yield the necessary information to determine the cross-over point from feature facilitation to episodic retrieval.

3   Saccadic priming effects in active visual search.

Hitherto this thesis has focused on repetition priming in key-press search tasks. Supplementary to the five experiments I present the results from two experiments. The first experiment explores priming effects in a visual search task involving saccadic eye-movement responses while the second serves as a control experiment.

3.1   Experiment 5 – Saccadic priming

Although the focus of visual attention can move covertly without eye-movements, there is a strong link between saccadic movements and visual attention. In the following experiment we explore priming effects in active visual search where responses are made with saccadic eye-movements rather than conventional key-press responses. In the second experiment we tested a large sample of subjects on a key-press version of the task to compare the two modes of responding.

3.1.1   Methods

Participants. A: Five students at the University of Iceland participated in the experiment. Three of which were naive to the purpose of the study while the other two were the first and second authors. All participants reported normal or corrected-to-normal vision.

Stimuli and apparatus. Stimuli were presented on a dual-monitor 2.4 GHz desktop computer. Stimuli were presented on an 85 Hz CRT monitor. Stimulus presentation was programmed with MATLAB™ using the Psychophysics Toolbox (version 3.0; Brainard, 1997; Pelli, 1997). Eye-movements were measured with a Cambridge Research Systems High-speed (250 Hz) Video Eyetracker and eye-movement data collected with the CRS toolbox for MATLAB™.

Any given trial contained four squares presented on an imaginary circle with a fixed radius of 7,8° visual angle. The squares were 2x2. Three of the squares served as distractors while one was the target item. The target was defined by a unique color while the distractor shared the same color. Colors varied randomly between trials and were red (15 cd/m^2), blue (7 cd/m^2), green (46 cd/m^2) or yellow (60 cd/m^2). A smaller black square (0,3°) was located centrally within all items and served as a landing point for saccadic movements (figure 10).

Procedure and design. All subject participated in at least 200 practice trials prior to data collection to familiarize them with the task, ensure correct fixation and practice blinking strategies. Observers were instructed to try to blink immediately after fixating a target to preserve the integrity of the eye movement signal during the central fixation and stimulus presentation intervals of the trials. At the start of each trial a grey fixation cross appeared for 500 ms. at the center of the screen. The cross then turned white for a period of 200-700 ms. Finally the cross turned back to grey and the stimulus items appeared on the monitor. The subjects then fixated to the odd-one-out item on the screen (defined by color). The stimuli were present on the screen for a total of 2500 ms. before the next trial started

(figure 10). Target and distractor colors as well as target location were determined randomly. Subjects participated in 12-35 blocks of a 100 trials each.
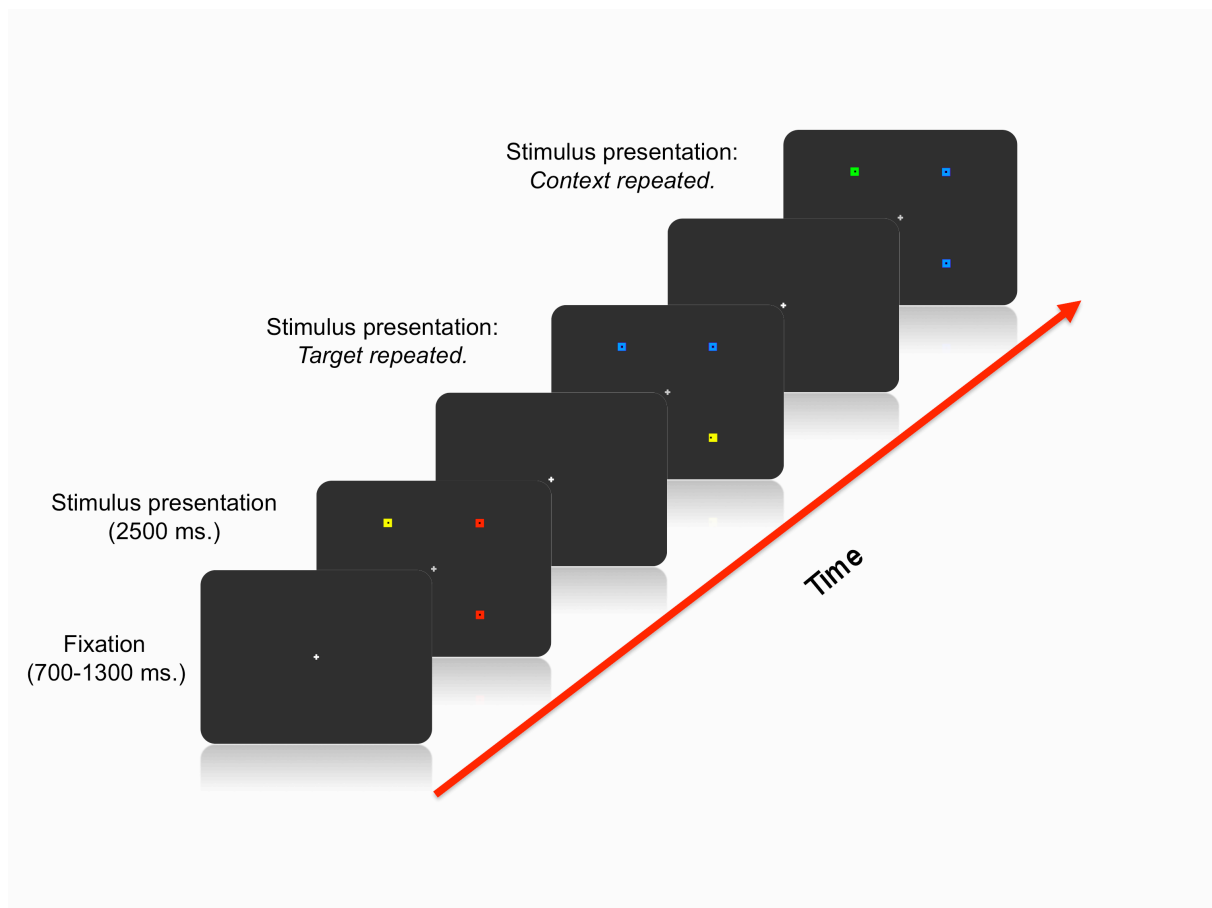
Figure 10. Examples of trials where either target or distractors (context) are repeated.

3.1.2 Results and discussion

A 2 by 2 repeated measures ANOVA with *target color repetition* and *distractor color repetition* and *mean reaction times* as the response variable revealed a marginally significant 6 ms. (F(1, 4)=7,235; p=0,055) facilitatory effect of distractor repetition while target repetition did not significantly facilitate reaction times (p=0,121). However, target repetition resulted in more response accuracy 1.7 pp (F(1 ,4)=20,863; p=0,01) but distractor repetition did not significantly facilitate correct responses (F(1, 4)=1,898; p=0,24). Neither analyses showed any interactions between the two variables (*p*=0,425 for reaction times and *p*=0,745 for accuracy). Repeating location did not exert significant effects on responses and was therefore ignored in this analysis.

While the significant effects reported here are (1) distractor repetition facilitates reaction times and (2) target repetition facilitates accuracy the data trends certainly indicate that both variables do facilitate both reaction times and accuracy. Neither response variable is very informative without considering the other because of their interdependence. A subject with a liberal response criterion will be fast with lower accuracy while a conservative subject will show the opposite effect. Therefore we calculated the *inverse efficiency* of search for all participants and conditions and analyzed the data to

get a more informative measure of how repetitions affect search efficiency. Inverse efficiency is calculated by dividing mean reaction times (RTs in ms.) with the correct response ratio (CRR) for the particular condition.

A 2 by 2 repeated measures analysis on the inverse efficiency coefficients revealed main effects of both target and distractor repetitions. The effects of distractor repetition were 11 ms./CRR ($F(1, 4)=31,851$; $p=0,005$) while target repetition effects were 10 ms./CRR ($F(1, 4)=9,466$; $p=0,037$). There was no interaction between the two variables ($p=0,586$).

These results indicate that priming effects between different variables, but importantly, the same dimensions can be independent and approximately additive (see figure 11).
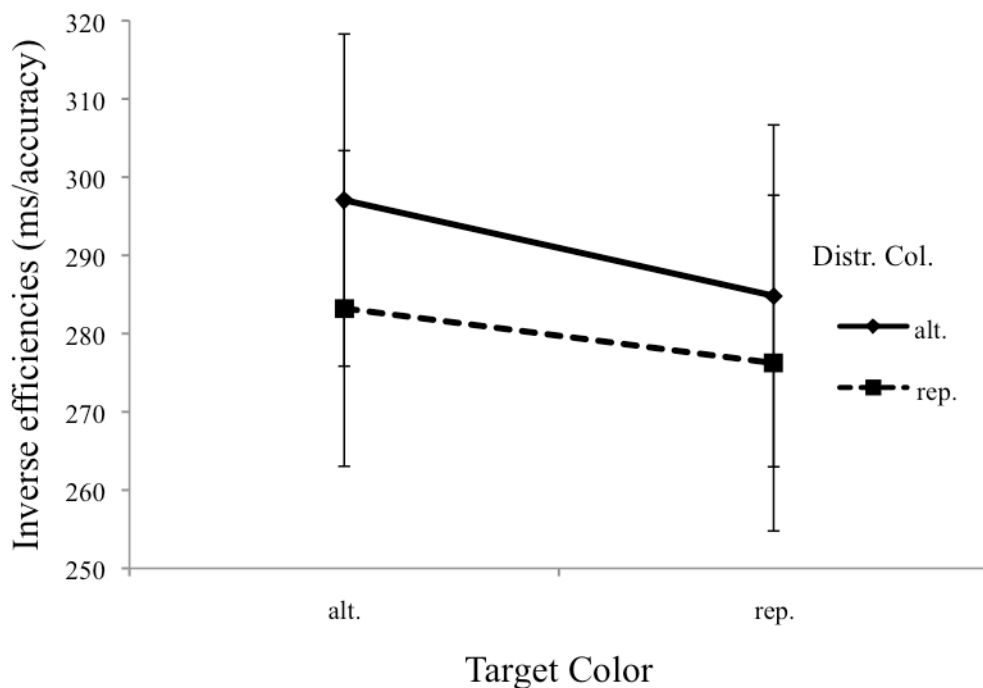
Figure 11. Inverse efficiency by repetition of target and distractor color . Error bars show ± 1 SEM.

This experiment has shown independent and additive effects of single dimension target and distractor priming in eye-movement data but most visual search tasks use key-press data. In experiment 2 we present a similar task but with key-press responses to see if our results generalize to different methods of responding.

3.2   Experiment 2 – A key-press version of the color priming task

The visual search task in Experiment 1 produced predictable results. Priming effects were small, independent between dimensions and the response time pattern was additive. These results support a feature facilitation account of priming which is the top candidate for explaining priming in efficient visual search tasks. However, most visual search task use key-press responses rather than saccadic responses. There are (to the authors knowledge) no published results from a key-press version of the task presented in experiment 1 in the visual search literature. Therefore we programmed such a

version to get a direct key-press comparison group. There are at least two ways to do that: (1) With a discriminatory key-press or (2) a present/absent judgment. Both choices have their advantages. A discriminatory response, such as right vs. left lateralization of the black fixation point within targets, forces the subjects to direct their eyes to the target and make a judgment. In the eye-tracking experiment subjects were of course forced to direct their gaze to the targets since that was the required response. However, this does add a judgment to the task (left vs. right lateralization), which was not present during the eye-tracking version. The present/absent judgment of a target does only requires a judgment of stimulus presence and therefore target fixation is unnecessary. Here we present results using the former option, a replication of experiment 1 with an added discriminatory response.

3.2.1 Methods

Subjects. Forty-one students at the University of Iceland participated in the experiment. Participation in the visual search task was mandatory in an undergraduate class on perception and cognition. The author got permission to use data from all students included in this study.

Stimuli and apparatus. Experiments were run on computers in computer labs at the University. Stimulus presentation and data collection was done using E-prime™.

The stimuli very similar to those in experiment 1 but because subjects used different computers and different monitors (LCD) luminance was not measured. However, the stimuli had the exact same RGB-values as those in experiment 1. In this experiment the subjects heads were not fixed on a chin-rest and therefore retinal stimulus size varied between subjects.

To collect responses with key-presses the experimental task demanded a discrimination response from subjects. The small black square within the target was therefore slightly lateralized to the left or right and subjects responded to the lateralization by pressing J (left) or L (right).

Procedure and design. The subjects received instructions on how to run the experiment through their personal university websites (*ugla.hi.is*). They followed these instructions to start the experiment at a time of their choice. When the experimental program running an instructions-screen appeared explaining the task at hand. Following the instructions participants completed 16 practice trials to familiarize themselves with the task. A screen announcing the start of the experiment was presented and subsequently 384 experimental trials were completed.

Some participants (n=3) completed two blocks of 384 trials while the rest completed one block.

3.2.2 Results and discussion

Initial analyses of the data indicated that, contrary to experiment 1, location repetition exerts effects on responses. Therefore the main analysis was a 2 by 2 by 2 repeated measures ANOVA with *target repetition, distractor repetition* and *location repetition* as the within-subject factors.

The analysis revealed no main effects of repetition. Looking at the means for the variables by themselves target repetition slowed down responses by 18 ms/CRR and distractor repetition by 24 ms/acc. These effects are not meaningful by themselves. In fact they can all be explained by a very large inhibitory effect when all three variables are repeated. This effect is large enough to disguise the priming effects. In figure 12A the effects of target and distractor repetition are shown when location is alternated from the last trial. Here we see a 38 ms/acc. priming effect of distractor repetition and a 15 ms/acc. effect of target repetition. When location is also repeated (figure 12B) we still see faster RTs when one of the other variables is also repeated but when the third variable is added we get a large (174 ms/CRR) inhibitory effect overshadowing the facilitatory effects. An interaction between all three variables was confirmed by the analysis ($F(1, 40)=22,847$; $p<0,001$). Interactions between all pairs of variables were also confirmed but the as shown in Figure 12 the three way interaction is by far the most interesting.
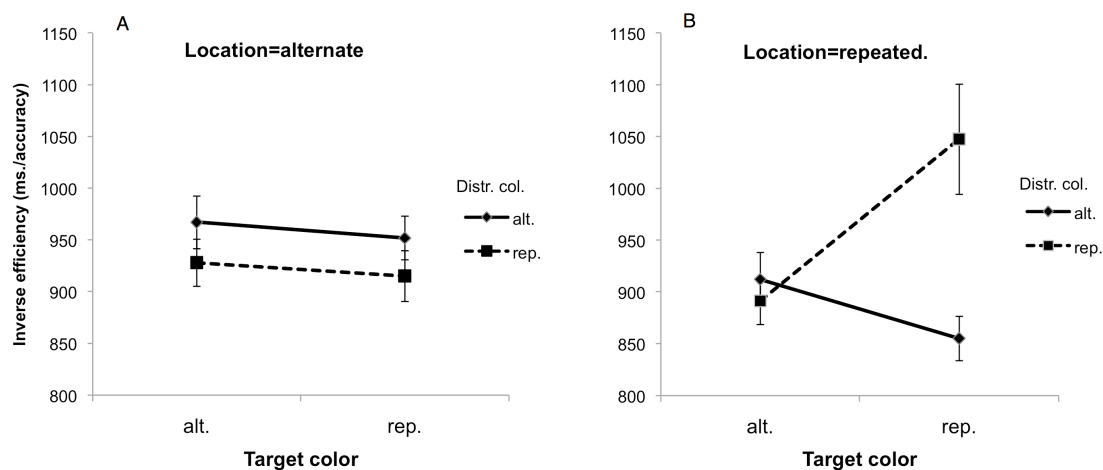
Figure 12. Inverse efficiencies by repetitions of target and distractor color. Panel A shows results when location is alternated and panel B when location is repeated. Error bars show ± 1 SEM.

This finding brings up several interesting points: (1) It is only found in the key-press version of the task suggesting that it has something to do with either the act of discrimination/decision making added to this task. Alternatively it is simply an artifact of pressing a key. In this context it is important to note that the effect was not dependent on a repetition of all features *and* repetition of response (left/right). Inhibition occurred in both response conditions. (2) The effect is obviously location specific and therefore we must interpret it in light of what we know about *inhibition of return*. However, there are reasons to be cautious since the effect is much larger than most IOR-effects (usually less than 60 ms.) and such effects are thought to peak at around 300-400 ms. after presentation and then gradually fading (Klein, 2000). In this experiments the stimulus display on trial *n+1* was presented at least 700 ms. after a response on trial *n*. Nevertheless the term IOR certainly describes the effect although it must noted that it was fully context dependent. This attribute of the inhibitory effect is in accordance with Klein and McInnes (1999) finding that IOR was not present when the "scene" of visual search was removed in a probed search experiment. In Klein and McInnes's study (1999) it was the background

that was manipulated but there is no reason to think that IOR can not be dependent on other context features, especially in an experiment where the stimulus locations are fixed throughout and covert attention can in theory be allocated to the four sites of presentation beforehand.

The inhibitory effect shares many features with IOR but is also in some sense a novel finding. Maljkovic and Nakayama (1996) showed that location could be facilitated by repetitions in a task in many ways similar to this one. In our experiment we do see trends towards location priming under all conditions except when the three variables are all repeated. Why our results are different is difficult to say. A first step towards explaining this effect would be to run an experiment with a detection task rather than a discrimination task to test a response-related hypotheses.

In the context of this thesis the results are mostly predictable. In the eye-tracking experiment and under most conditions of the key-press experiment we see predictable patterns. Priming effects independent of each other and cumulating in an additive manner. There are no holistic (or episodic) facilitatory effects as predicted by Huang *et al.'s* (2004) theory of priming in visual search. In fact the only holistic effect is the large inhibitory effect, which is a polar-opposite of the episodic effects reported by Huang *et al.*

3.3 Conclusions

Although episodic/holistic effects of repetition in visual search may explain some results in the literature, the results from the two experiments do not introduce a need for such an explanation. A feature facilitation account of priming can explain most of the data (Maljkovic and Nakayama, 1994, 1996, Kristjánsson, 2006) and the exception, a large inhibitory effect when the whole scene is repeated may be accounted for by IOR. Priming effects and IOR are not assumed to share a mechanism and a clash between them is not implausible. Such a clash may in fact be very interesting since it has the potential to disguise priming effects if IOR is not controlled for in experimental design and/or during statistical analysis. This may be the case in some of the published literature on priming effects in visual search.

There are two major flaws to consider in the experiments. In experiment 1 the sample is only 5 subjects. Each subject does complete a lot of trials but if the IOR phenomenon observed in experiment 2 is found in some subjects but not others our small sample may by coincidence be biased. In the second experiment we have a lot of subjects but not a lot of trials for each subject. This leaves relatively few trials for each condition when we analyze the data in a 2 by 2 by 2 analysis. The results should therefore be regarded as hypothesis generating rather than a fact of human visual perception and attention.

4   References

Ásgeirsson, Á.G. and Kristjánsson, Á. (2008). Episodic retrieval accounts of priming in visual search explain only a limited subset of findings on priming. *Perception, 37* (suppl.), 93-94.

Becker, S. I. (2008a). The mechanism of priming: episodic retrieval or priming of pop-out? *Acta Psychologica (Amst.), 127*, 324-339.

Becker, S. I. (2008b). The stage of priming: Are intertrial repetition effects attentional or decisional? *Vision Research, 48*, 664-84

Becker, S. I. and Horstmann, G. (2009). A feature weighting account of priming in conjunction search. *Attention, Perception & Psychophysics, 71*, 258-272.

Bichot, N.P. and Schall, J.D. (2002). Priming in macaque frontal cortex during pop-out visual search: Feature-based facilitation and location-based inhibition of return. *Journal of Neuroscience, 22,* 4675-4685.

Brainard, D. (1997). The psychophysics toolbox. *Spatial Vision, 10,* 433-436.

Bravo, M. and Nakayama, K. (1992). The role of attention in different visual-search tasks. *Perception & Psychophysics, 56,* 465-472.

Campana, G., Cowey, A., and Walsh, V. (2002). Priming of motion direction and area V5/MT: a test of perceptual memory. *Cerebral Cortex, 12*, 663-669.

Campana, G., Cowey, A., and Walsh, V. (2006). Visual area V5/MT remembers "what" but not "where". *Cerebral Cortex, 16*, 1766-1770.

Comtois, R. (2003). *Vision Shell PPC* [Software libraries]. Cambridge, MA: Author

Geng, J.J., Eger, E., Ruff, C., Kristjánsson, Á., Rothsthein, P. and Driver, J. (2006). On- line attentional selection from competing stimuli in opposite visual fields: Effects on human visual cortex and control processes. *Journal of Neurophysiology, 96*, 2601-2612.

Geyer, T., Müller, H.J., and Krummenacher, J. (2006). Cross-trial priming in visual search for singleton conjunction targets: Role of repeated target and distractor features. *Perception & Psychophysics, 68*, 736-749.

Goolsby, B.A. and Suzuki, S. (2001). Understanding priming of color-singleton search: Roles of attention at encoding and "retrieval". *Perception & Psychophysics, 63*, 929-944.

Hillstrom, A.P. (2000). Repetition effects in visual search. *Perception & Psychophysics, 62*, 800-817.

Horowitz, T.S. and Wolfe, J.M. (1998). Visual search has no memory. *Nature, 394,* 575-577.

Huang, L., Holcombe, A.O., and Pashler, H. (2004). Repetition priming in visual search: Episodic retrieval, not feature priming. *Memory & Cognition, 32*, 12-20.

Huang, L. and Pashler, H. (2005). Expectation and repetition effects in searching for featural singletons in very brief displays. *Perception & Psychophysics, 67*, 150-157.

Hulleman, J. (2009). No need for inhibitory tagging of locations in visual search. *Psychonomic Bulletin & Review, 16(1),* 116-120.

Julesz, B. (1984). A brief outline of the texton theory of human vision. *Trends in Neurosciences, 7*, 41-45.

Klein, R.M. (1988). Inhibitory tagging facilitates visual search. *Nature, 334,* 430-431.

Kelin, R.M. and McInnes, W.J. (1999). Inhibition of return is a foraging facilitator in visual search. *Psychological Science, 10(4),* 346-352.

Klein, R.M. (2000). Inhibition of return. *Trends in Cognitive Sciences*, *4(4),* 138-147.

Kristjánsson, Á. (2000). In search of remembrance: Evidence for memory in visual search. *Psychological Science, 11(4),* 328-332.

Kristjánsson, Á., Wang, D. and Nakayama K. (2002). The role of priming in conjunctive visual search. *Cognition, 85*, 37-52.

Kristjánsson, Á., Vuilleumier, P., Malhotra, P., Husain, M., and Driver, J. (2005). Priming of color and position during visual search in unilateral spatial neglect. *Journal of Cognitive Neuroscience, 17*, 859-873.

Kristjánsson, Á. (2006a). Rapid learning in attention shifts - A review. *Visual Cognition, 13*, 324-362.

Kristjánsson, Á. (2006b). Simultaneous priming along multiple dimensions in visual search task. *Vision Research, 46*, 2554–2570.

Kristjánsson, Á. (2006c). Surface assignment modulates object-formation for visual short-term memory. *Perception, 35*, 865-881

Kristjánsson, Á., Vuilleumier, P., Schwartz, S., Macaluso, E. and Driver, J. (2007). Neural basis for priming of pop-out revealed with fMRI. *Cerebral Cortex, 17*, 1612-1624.

Kristjánsson, Á. (2008). "I know what you did on the last trial" – a selective review of research on priming in visual search. *Frontiers in Bioscience, 13*, 1171-1181.

Kristjánsson, Á., and Driver, J. (2008). Priming in visual search: Separating the effects of target repetition, distractor repetition and role-reversal. *Vision Research, 48*, 1217-1232.

Kristjánsson, Á., Ingvarsdóttir, Á. and Teitsdóttir, U. D. (2008). Object- and feature-based priming in visual search, *Psychonomic Bulletin & Review, 15*, 378-384.

Kristjánsson, Á. (2009). Independent and additive repetition priming of motion direction and color in visual search. *Psychological Research, 73*, 158-166.

Kristjánsson, Á. and Campana, G. (2010). Where perception meets memory: A review of repetition priming in visual search tasks. *Attention, Perception & Psychophysics,72*, 5-18.

Lamy, D. Bar-Anan, Y. and Egeth, H. E. (2008). The role of within-dimension singleton priming in visual search . *Journal of Experimental Psychology: Human Perception & Performance, 34*, 268 - 285.

Lamy, D., Yashar, A. and Ruderman, L. (2010). A dual-stage account of inter-trial priming effects. *Vision Research, 50*, 1396-1401.

Maljkovic, V. and Nakayama, K. (1994). Priming of pop-out: I. Role of features. *Memory and Cognition, 22*, 657-672.

Maljkovic, V. and Nakayama, K. (2000). Priming of pop-out: II. The role of position. *Perception & Psychophysics, 58(7),* 977-991.

Meeter, M. and Olivers, C.N.L. (2006). Intertrial priming stemming from ambiguity: A new account of priming in visual search. *Visual Cognition, 13*, 202-222.

Nakayama, K., Maljkovic, V., and Kristjánsson, Á. (2004) Short term memory for the rapid deployment of visual attention. In M.S. Gazzaniga (ed.), *The Cognitive Neurosciences, 3rd edition*. Cambridge, MA: MIT Press.

Olivers, C. N. L., and Meeter, M. (2006). On the dissociation between compound and present/absent tasks in visual search: Intertrial priming is ambiguity driven. *Visual Cognition, 13*, 1-28

Pelli, D.G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10(4),* 437-442.

Peterson, M.S., Kramer, A.F., Wang, R.F. Irwin, D.E. and McCarley, J.S. (2001). Visual search has memory. *Psychological Science, 12 (4),* 287-292.

Saevarsson, S., Jóelsdóttir, S., Hjaltason, H. and Kristjánsson, Á. (2008). Repetition of distractor sets improves visual search performance in hemispatial neglect. *Neuropsychologia, 45,* 1161-1169.

Sigurdardottir, H.M., Kristjánsson, Á. and Driver, J. (2008). Repetition streaks increase perceptual sensitivity in brief visual search displays. *Visual Cognition, 16,* 643-658.

Theeuwes, J., and Kooi, F. L. (1994). Parallel search for a conjunction of contrast polarity and shape. *Vision Research, 34,* 3013-3016.

Treisman, A.M. and Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology, 12,* 97-136.

Vogel, E. K., Woodman, G. F., and Luck, S. J. (2001). Storage of features, conjunctions, and objects in visual working memory. *Journal of Experimental Psychology: Human Perception & Performance, 27,* 92-114.

Walsh, V., Le Mare, C., Blaimire, A., and Cowey, A. (2000). Normal discrimination performance accompanied by priming deficits in monkeys with V4 or TEO lesions. *NeuroReport, 11,* 1459-1462.

Wang, D., Kristjánsson, Á., and Nakayama, K. (2005). Efficient visual search without top-down or bottom-up guidance. *Perception & Psychophysics, 67,* 239-253.

Wolfe, J.M., Cave, K.R. and Franzel, S.L. (1989). Guided search: An alternative to the feature integration model for visual search. *Journal of Experimental Psychology: Human Perception and Performance, 15(3),* 419-433.

Wolfe, J.M. and Pokorny, C. (1990). Inhibitory tagging in visual search: a failure to replicate. *Perception & Psychophy*sics, *48(4),* 357-62

Wolfe, J.M. (1994). Guided search 2.0: A revised model of visual search. *Psychonomic Bulletin & Review, 1(2),* 202-238.

Wolfe, J. M., Friedman-Hill, S. R., and Bilsky, A. B. (1994). Parallel processing of part–whole information in visual search tasks. *Perception & Psychophysics, 55,* 537-550.

Wolfe, J.M. and Gancarz, G. (1996). *Guided search 3.0. Basic and clinical applications of vision science.* Dordrecht, Netherlands: Kluwer Academic. 189-192.

Wolfe, J.M. (1998). What can 1 million trials tell us about visual search? *Psychological Science, 9(1),* 33-39.

Wolfe, J.M. (2007). Guided search 4.0: Current progress with a model of visual search. In W. Gray (Ed.). *Integrated Models of Cognitive Systems* (pp. 99-119). New York: Oxford.

Xu, Y. (2002a). Feature integration across parts in visual search. *Perception, 31,* 1335-1347.

Xu, Y. (2002b). Encoding color and shape from different parts of an object in visual short-term memory. *Perception & Psychophysics, 64,* 1260-1280.