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Simultaneous priming along multiple feature dimensions in a visual search task

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Abstract

What we have recently seen generally has a large effect on how we consequently perceive our visual environment. Such priming effects play a surprisingly large role in visual search tasks, for example. It is unclear, however, whether different features of an object show independent but simultaneous priming. For example, if the color and orientation of a target item are the same as on a previous trial, is performance better than if only one of those features is repeated? In other words this paper presents an attempt at assessing the capacity of priming for different feature dimensions. Observers searched for a three featured object (a gabor patch that was either redscale or greenscale, oriented either to the left or right of vertical and of high or low spatial frequency) among distractors with different values along these feature dimensions. Which feature was the target defining feature; which was the response defining feature and which was the irrelevant feature, was varied between the different experiments. Task relevant features (target defining, or response defining) always resulted in priming effects, while when spatial frequency or orientation were task irrelevant neither resulted in priming, but color always did, even when task irrelevant. Further experiments showed that priming from spatial frequency and orientation could occur when they were task irrelevant but only when the other feature of the two was kept constant across all display items. The results show that simultaneous priming for different features can occur simultaneously, but also that task relevance has a strong modulatory effect on the priming.
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1. Introduction

In recent years, it has become increasingly clear that priming plays a larger role in visual perception than many had perhaps previously thought (see e.g., Kristjánsson, 2006; Nakayama, Maljkovic, & Kristjánsson, 2004, for reviews). In general, observers seem to be preferentially drawn to those items that share features with a preceding behaviorally relevant stimulus. Such priming has, for example, been found both in visual search tasks where the target "pops out" of the display (Goolsby & Suzuki, 2001; Huang, Holcombe, & Pashler, 2004; Kumada, 2001; Maljkovic & Nakayama, 1994; Meeter & Olivers, 2006; Muller, Krummenacher, & Heller, 2004; Theeuwes,

Riemann, & Mortier, in press), as well as in more challenging search task where the target is not as easily found (Hillstrom, 2000; Kristjánsson, Wang, & Nakayama, 2002; Wang, Kristjánsson, & Nakayama, 2005). Similarly, repeated position of task relevant items has been shown to decrease response latencies (e.g., Kristjánsson, Vuilleumier, Malhotra, Husain, & Driver, 2005; Maljkovic & Nakayama, 1996). It has furthermore been shown that not only do the features, or the position of the target in each case result in priming effects, but so does the context that the task is presented in (Kristjánsson et al., 2002; Wang et al., 2005). For example, repetition of distractor sets in visual search tasks can lead to considerably faster performance than otherwise (Kristjánsson & Driver, 2005) and this priming of *search context* is independent of whether the target is repeated or not, and can even occur between adjacent trials where no target is present on either trial.

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At the same time, objects that must be ignored on one trial (e.g., distractors in a visual search task), lead to worse performance when the ignored stimulus must then be acted upon in some way as a target (see e.g., DeSchepper & Treisman, 1996; Kristjánsson & Driver, 2005; Maljkovic & Nakayama, 1994; Nakayama et al., 2004; Tipper, 1985, 1992), showing that what has been ignored tends to be ignored subsequently and that more effort is required to attend to a particular stimulus if it was previously ignored than otherwise. Such effects are, most likely, related to the priming of search context since if the context is repeated it is likely that it can be ignored faster than a new search context, as mentioned before (Kristjánsson & Driver, 2005).

Priming in visual search cannot be simply attributed to response repetition and task switching (Kristjánsson, Sigurðardóttir, and Driver, unpublished data; Maljkovic and Nakayama, 1994). In Kristjánsson et al. (unpublished data) increases in sensitivity to the primed feature were observed as measured by the *response bias* free measures of signal detection theory (e.g., Wickens, 2001), in other words, d-prime (a measure of sensitivity independent of response bias) increased with repetition of target color. We also found that performance on a discrimination task on the pop-out item in a visual search array improved as the same target color was repeated between trials and suffered when a different colored target was presented subsequently, showing that the visual analysis of these display items is enhanced following the repetition of the features of the behaviorally important item. This shows that priming does not simply reflect the quickening of the response selection process. Priming effects with such brief displays appear however, not to be particularly strong when measured with simple feature detection tasks (Huang & Pashler, 2005). In addition, priming seems to be particularly strong when ambiguity is involved, for example, when there is uncertainty about the target identity Olivers and Meeter (2006).

1.1. What can priming tell us about the visual system?

Priming has the potential to yield insights into how the visual system operates, for a number of reasons. Priming may, for example, be an indication of how long a trace of the representation of a behaviorally important stimulus lasts in the visual system. How easily priming can be overcome, or in other words, how easy it is to switch from one "set" to another, may inform us of how attending to one item in the visual field can influence how we subsequently orient towards other items, and thus inform us about how we orient (or reorient) towards the behaviorally important items surrounding us.

Investigations of priming may also help us find out at what stage in the visual process representations of stimuli occur. For example, imaging studies (fMRI) on priming in visual search tasks (Kristjánsson, Vuilleumier, Husain, Macaluso, & Driver, 2004; Yoshida, Tsubomi, Osaka, & Osaka, 2003) have shown how priming of color and posi-tion is correlated with decreases in the blood–oxygen level dependent (BOLD)[1] signal in relatively early visual areas, and color priming shows such repetition decreases in the BOLD signal in areas in the fusiform cortex concerned with the processing of color (e.g., V4/V8; Kristjánsson et al., 2004). Both position and color priming lead to similar activation decreases as a function of priming in regions that are often associated with the operation of visual attention in frontal and parietal cortices. This result indicates that priming is reflected at different levels of analysis: some parts of the human brain show *dimension* related priming effects (e.g., either for position repetition *or* for color) while other areas show effects at a more global level of analysis, perhaps priming related to the repetition of whole objects. There is indeed behavioral evidence that priming in a visual search task can occur both for single features (Kristjánsson, 2006; Maljkovic & Nakayama, 1996) as well as at the level of whole objects (Huang et al., 2004).

Furthermore priming may inform and constrain our ideas of the evolutionary aspects of visual processing since it seems likely that there is an evolutionary benefit to priming since the behaviorally important objects in our visual environment remain relatively stable over time, and we tend to reorient (and refoveate) the important items in our environment over and over again (see e.g., Ballard, Hayhoe, Li, & Whitehead, 1992). For example, prey keeping track of a potential predator will benefit greatly from being able to reorient quickly to that predator, if it loses sight of it momentarily (see, for example, discussion in Kristjánsson & Nakayama, 2003). The things that are important to us and we must thus attend to, tend to be relatively stable over time.

Finally, priming seems to be relevant to long standing debates in the literature on visual attention, in particular with regard to theories of visual search (e.g., Duncan & Humphreys, 1992; Treisman & Gelade, 1980; Wolfe, 1994). An important component of these models is the role of *top–down guidance* in determining how easily particular visual search targets are found. This concept entails that an observers "search template" can be biased towards certain features which the target contains. Some surprising results (e.g., Kristjánsson et al., 2002; Pinto, Olivers, & Theeuwes, 2005; Theeuwes et al., in press; Wang et al., 2005) have surfaced, however, when top–down guidance and between-trial priming have been contrasted with one another. It seems that intertial priming can account for large portions of effects that have often been thought to reflect the contribution of top–down guidance although estimates of exactly *how much* of putative top–down effects are accounted for by priming differ somewhat (see e.g., Wolfe, Butcher, Lee, & Hyle, 2003 for a different view). What is clear, however, is that intertrial priming should play a larger role in theories of visual search than it currently does.

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[1] Such decreases in the BOLD signal are commonly seen when the same stimulus is repeatedly presented in the context of an fMRI experiment (see e.g., Grill-Spector & Malach, 2001; Henson & Rugg, 2003; Kourtzi & Kanwisher, 2001).

1.2. The current goals

The aim of the research in this paper is to examine how many types of features can lead to priming effects as they are repeated simultaneously on the same object, or in other words to assess the *capacity* of priming. We know, for example, that priming of color and position can occur simultaneously and independently (Maljkovic & Nakayama, 1996; see also discussion in Nakayama et al., 2004). Maljkovic and Nakayama found that as the color of the target was repeated from trial to trial and faster response times were observed, the response times also decreased if the target appeared in the same location as before. Here, the topic of investigation is simultaneous priming of different visual features of a single target presented among distractors.

This question can lead to an answer to the question of whether on the one extreme a central "priming center" is responsible for the priming effects or whether on the other hand the priming occurs in regions devoted mainly to the analysis of one particular feature dimension, as some findings from the aforementioned imaging results might suggest, although the same studies also indicate that there are also considerable similarities in the neural correlates of priming for different aspects of a particular stimulus; in particular the fronto-parietal attentional network.

While as is very often the case in cognitive science, the truth most likely lies somewhere in between the two extreme options, answers to such questions may lead to important insights about how the brain operates. The aforementioned neuroimaging study (see Kristjánsson et al., 2004) indicates indeed that the correct answer is somewhere between the two extremes since on the hand the results revealed regions that showed shared repetition suppression for both color and position priming while there were also regions that were specific to one type of priming as mentioned above.

Many authors have discussed how the computations carried out in the human brain are "massively parallel"—with many types of ongoing processes occurring simultaneously—the sum of which constitutes what we might call our consciousness (e.g., Dennett & Kinsbourne, 1992; Fodor, 1983; McClelland & Rumelhart, 1987). Thus, analysis of the color of a particular stimulus may occur simultaneously with analysis of the orientation of stimuli in separate functional entities devoted to such analyses (in the literature on visual search often termed *feature maps*, which can be a useful abstraction if the emphasis is on their functional properties rather than any sort of anatomical localization of those feature maps).

As mentioned before, it has previously been shown that parallel build-up of priming occurs for location and position (Maljkovic & Nakayama, 1996; see discussion in Nakayama et al., 2004). While these results show that parallel build up of vastly different properties of the stimulus like color and location can build up simultaneously, one could ask how many properties can show such simultaneous and parallel priming? Do they need to be of rather

different dimensions? Is there a saturation level for priming of different properties? In other words given an object that has several features, is there a point at which repetition of features does not result in any more benefit? Do features that share neural circuits for their processing show simultaneous build-up of priming or do the neural networks show signs of "saturation" of priming?

1.3. The current experiments

The experimental procedure involved a visual search task with stimuli that varied along three dimensions. Gabor patches, where the color levels of the sinusoid multiplied by the Gaussian patch, varied either from dark to bright green or from dark to bright red, were used (see Methods and Figs. 1 and 2 for further details on the stimuli). There were thus three critical features of the gabor target that were looked at in terms of repetition priming: *orientation* of the sinusoid making up the gabor, the *spatial frequency* of that same sinusoid and the *color* scale of the gabor patch (dark green to light green or dark red to light red). Using a 3-featured stimulus allows independent variation of the task relevance of the features to assess how these features prime independently of one another, while always using the exact same type of stimulus. In the first three experiments the tasks were to find the *oddly colored* gabor patch (the *target defining* feature in Experiment 1), the *oddly oriented* gabor patch (the target defining feature in Experiment 2), and the gabor patch with the *odd spatial*
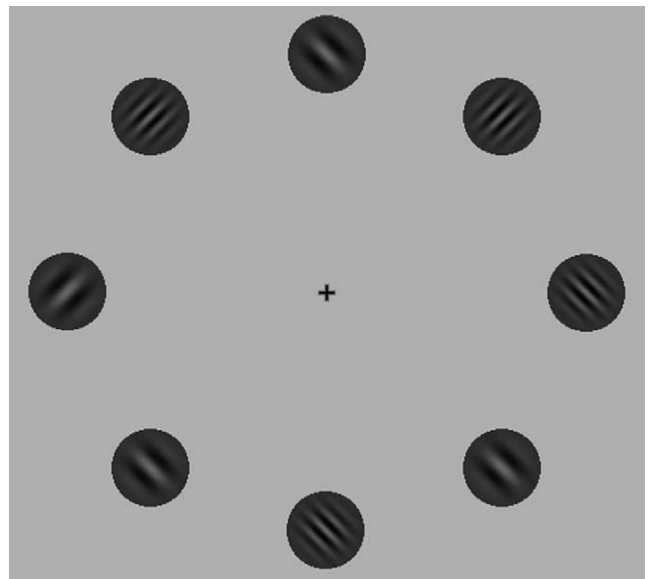

Fig. 1. A sample stimulus display for a single trial from the experiments in the paper. The stimuli could vary along three dimensions in Experiments 1 to 3 (colorscale of the gabor patch [red or green, not indicated here], orientation and spatial frequency) and along two dimensions in Experiments 4 and 5 (color and orientation in Experiment 4 and color and spatial frequency in Experiment 5). The target was always the odd-one-out along a particular target defining feature dimension, which varied among the five different experiments in the paper. See the individual methods sections for each experiment for further details on methodology.
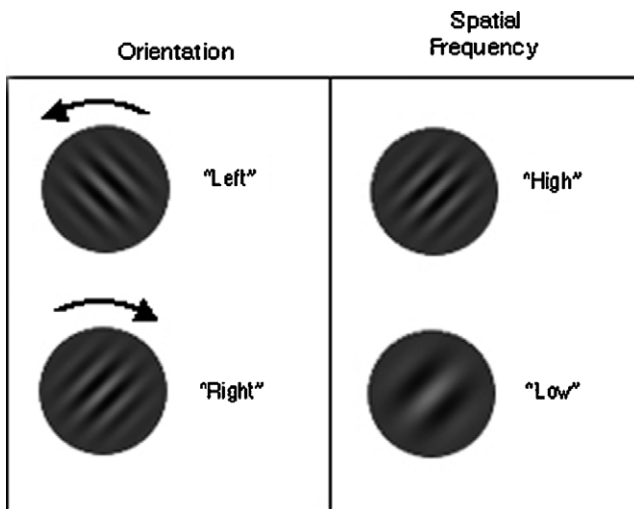
Fig. 2. The two possible values for the gabor patches along the feature dimensions orientation and spatial frequency used in the experiments in this paper.

frequency ("high" or "low" spatial frequency, the target defining feature in Experiment 3). Furthermore, one of the two remaining features (apart from the target defining feature) was the *response defining* feature, so that in Experiment 1 the task was to answer what the *orientation* of the target was once it had been found, in Experiment 2 the task was to indicate the *spatial frequency* of the target gabor patch and in Experiment 3 the task was to indicate the *color* of the target gabor. This procedure means that in each experiment one of the features was *irrelevant* to the task, which can provide insights into what happens to task-irrelevant, or ignored information in terms of repetition priming. First, the question was which of the feature dimensions of the target gabor patch lead to priming as that feature is repeated on the target. Second, the effects of which of the target features are task relevant in each case was assessed. To better enable comparison between the different experiments presented here, the same three observers participated in all five experiments presented in the paper, and the total time of data acquisition for all experiments was kept as short as possible.

Priming for all the three features that were used has been independently observed before. Maljkovic and Nakayama (1994, 1996) have shown priming of color and spatial frequency, and Kristjánsson et al. (2002) and Hillstrom (2000) have shown priming for orientation albeit with bars rather than gabors, as are being use here. It has, however, never before been addressed how these feature priming effects interact with one another.

2. Experiment 1—Target defining feature: Color; response defining feature: Orientation

In the first experiment the critical target defining feature was color, while the response defining feature was orientation. The "irrelevant" feature in this case was thus spatial frequency. The critical question was whether these dimen-

sions would show parallel build up of priming. Strong priming effects from repetition of target color were fully expected since this was the "pop-out feature" by which the target could be distinguished from the distractors. Priming following orientation repetition was also expected, since the task involved indicating whether the target was oriented to the right or to the left. The main unknown was whether there would be priming for spatial frequency, the irrelevant feature. There are at least three possible scenarios. The first possibility is that there would be no repetition priming of spatial frequency for the reason that spatial frequency was simply ignored and not processed to any extent that would allow priming to develop (see Experiments 4 to 5 below for further investigations of this possibility). It is also possible that no priming for spatial frequency would be seen, but not because spatial frequency was ignored but because priming had reached some saturation point, or "maximum capacity", a possible reason being that analysis of orientation nulls any potential priming from repetition of spatial frequency. The third possibility is that priming would indeed be seen for spatial frequency showing that priming of color, spatial frequency and orientation can occur simultaneously, even if one of the features is irrelevant to the task.

In this first experiment, the task of the observers was to find the oddly colored item (either the redscale or the greenscale gabor), and indicate its orientation by pressing the appropriate key. The distractors were of the other color, so that if the target was a redscale gabor, all the distractors were greenscale gabors, and vice versa.

2.1. Methods

2.1.1. Participants

Three observers participated in the experiment. Two of them were unaware of the purpose of the experiment while one of the observers was the author. They all had either normal vision or normal vision when the optics of their eyes were supplemented with a corrective lens. Each observer received rather extensive practice on the task (at least 300 trials, and until they were quite confident about performing the task).

2.1.2. Stimuli

The stimuli were Gabor patches (a sinusoid multiplied by a two dimensional Gaussian patch) that were either red so that their color varied sinusoidally from dark red (6.3 cd m^{-2}) to light red (24.7 cd m^{-2}), in the case of a "redscale" gabor and from dark green (5.9 cd m^{-2}) to light green (25.3 cd m^{-2}) in the case of a "greenscale" gabor. The orientation of the sinusoid within the gabor patch was either 45 arc deg to the left or right of the vertical ("left" or "right" are the somewhat arbitrary terms used from here on in, but "left" simply means that the gabor was rotated counter-clockwise from vertical by 45 arc deg, and "right" means that the gabor was oriented by the same distance in the other direction, see Fig. 2). The eight gabors were spaced evenly on

an imaginary circle with a radius of 7.3 arc deg away from the screen centre where a black fixation cross (0.5 cd m^{-2}) was at dead centre. The stimuli were presented on a light grey (22.4 cd m^{-2}) background. There was always one odd-one-out gabor (the target) defined by color, so that if the target was greenscale all the other items were redscale, and vice versa. The colorscale of the target gabor (red or green) was determined completely randomly for each trial. The orientation and spatial frequency of each item was determined randomly on each trial, but with the constraint that there were always four each oriented to the left or right, and four each of high and low spatial frequency. The sinusoid constituting the gabors of "low" spatial frequency was 1.8 cycles per degree (cpd) of visual angle while the "high" spatial frequency gabors were 3.1 cpd. The size of the gabor patches was 1.8 arc deg—at the edges the brightness values for the gabors were at the midpoint value of the green scale or redscale, depending on its color. The stimuli were presented on an 85 Hz CRT display with a screen resolution of 768 by 1024 pixels, driven by a standard video card on a G4 PowerMac. The *Vision Shell* library for the C programming language was used for stimulus generation (Comtois, 2003).

2.1.3. Procedure

Each trial started with the presentation of the fixation cross on the light grey background. One thousand two hundred to 1700 ms afterwards (determined randomly for each trial) the eight stimuli were presented until the subject responded. If the gabor was oriented to the left the subject was told to press "4" on the numeric keypad of a standard keyboard, while if the gabor was oriented to the right they were told to press "6". The meaning of "right" and "left" was explained to the observers before data collection started (see also Fig. 2). Visual feedback was given after each trial, depending on whether the response was correct (in which case "!!OK!!" was presented in black on the screen) or incorrect (in which case "!!XX!!" was presented in black on the screen following the response). Each observer participated in 3000 trials, run in blocks of 100 trials. Such a large number of trials was required to get a reliable set of results, since the effects of three different repetition types was tested and because the effects of 0, 1, 2 and 3 or more repetitions of the same stimulus types were investigated. Only trials on which the observers responded correctly were used in the analyses of response times.

2.2. Results and discussion

The response times for the three observers can be seen in Fig. 3 as a function of how often each feature on the target was repeated. The results are shown for 0, 1, 2 or 3 and more repetitions of the feature in each case. The figure shows that there is a relatively large decrease in response times as the color of the target is repeated and a considerable (albeit smaller than for color) drop in response times as orientation is repeated. On the other hand, there is no
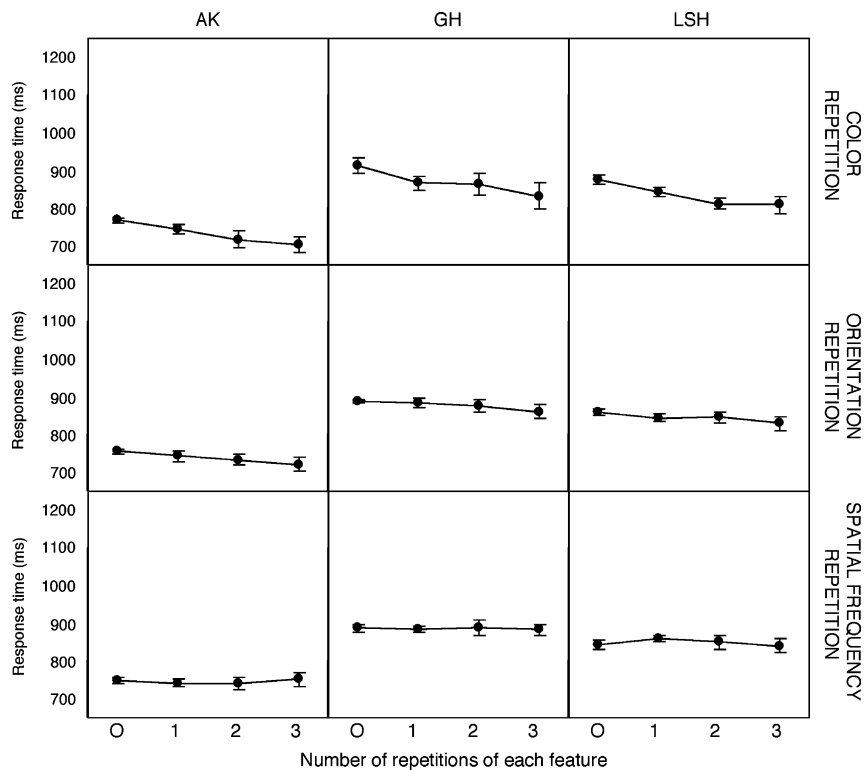

Fig. 3. The results of Experiment 1. The figure shows the response times as the different features in the experiment were repeated for the three observers (by columns). The results are shown for 0, 1, 2 or 3 and more repetitions of each feature on the target. The first row shows the response times as a function of repetition of color of the target; the second row shows performance as a function of the repetition of the target orientation, and the third row represents response times as a function of the repetition of the spatial frequency of the target. The error bars show the standard error of the mean for each datapoint.

evidence that response times decreased as the spatial frequency of the target was repeated, for any of the observers. Fig. 4 then shows the *average* effect of repetition upon the response times. The averages are obtained by taking the mean of the three differences between performance as a function of feature repetition (no repetition minus 1 repetition; 1 repetition minus 2 repetitions and 2 minus 3 and more repetitions) for each stimulus dimension and then dividing by three. The analyses in Fig. 4 show essentially the same pattern as the graphs in Fig. 3, that there is strong priming as color is repeated and considerable priming for orientation repetition, but no priming for spatial frequency repetition for any of the observers. Observer AK gave the wrong response on 3.1% of the trials, GH on 2.3% and LSH on 2.6% of the trials. Error trials were not used in the analyses of response times.

To summarize, the results show strong color priming as expected, as color was the pop-out, or target defining feature, and there is also relatively strong priming for orientation, not as strong as for color though.[2] There are two possible reasons for this, first, it is likely that orientation was not as salient a discriminating feature for the individual stimuli as color was, given that the color of the target was unique in the display, whereas the orientation was randomly determined for each item from the two possible ones ("left or right", see Section 2.1). Another reason to think that orientation was not as salient a feature as color are the results for Experiment 2 below which indicate that the search for a uniquely *oriented* target was slightly slower than the search for a uniquely *colored* target. Second, it is possible that the target defining feature in each case yields stronger priming than a task relevant feature. There is further discussion of this issue below.

On the other hand, there was no evidence for any priming of spatial frequency (see Figs. 3 and 4). Response times did not become faster as the spatial frequency of the target is repeated, at least when that feature is task irrelevant in this context (recall that Maljkovic & Nakayama, 1994 have shown that such priming effects for spatial frequency *can* occur when spatial frequency is the target distinguishing, or the "pop out" feature). So far, though, the results cannot discriminate between the possibilities that either there is no priming since spatial frequency was simply ignored

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[2] Maljkovic and Nakayama (1994) found no priming from *task* features (or response defining features) in their studies. All of their tasks required high acuity resolution for their analysis, however, (such as locating the notch cut off a diamond or the Vernier acuity of a spatial frequency target). In seeming contrast there is relatively strong priming for the response feature in this study. In the current experiments, however, orientation, spatial frequency and color can be resolved rather easily given the values of those features that are contrasted and thus do not count as high acuity aspects of the stimuli so it is perhaps not particularly surprising that priming is seen for these features. It should be noted, however, that the effects of task feature repetition are confounded with response repetition (the button to be pressed was the same when the feature value was the same) but disambiguating the two was not the aim of the current study, but see however, Experiments 4 and 5, which have some bearing on this issue.
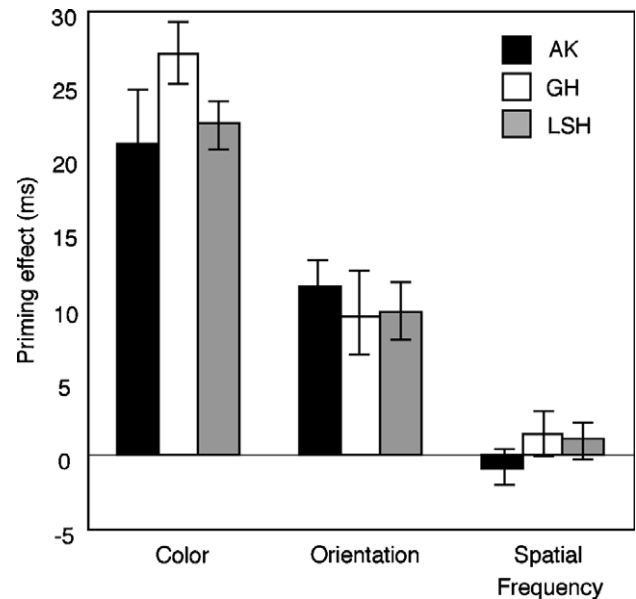

Fig. 4. Priming effects for the three types of repetition (color, orientation and spatial frequency) from Experiment 1. The averages are obtained by taking the mean of three differences between performance as a function of feature repetition (summing no repetition minus 1 repetition, 1 repetition minus 2 repetitions and 2 minus 3 or more repetitions and then dividing this sum by three). The error bars show the standard error of the mean for this difference.

or that priming does not develop since a saturation point for priming was reached. These questions are addressed in the experiments that follow.

3. Experiment 2—Target defining feature: Orientation; response defining feature: Spatial frequency

Experiment 1 showed that when the target defining feature was color and the response defining feature was orientation, a repetition benefit (or priming) was seen for both those features but no repetition benefit was seen for the irrelevant feature (in this case spatial frequency). The results raise the question of whether some saturation level or maximum priming capacity was reached. In Experiment 2 the aim was to see whether orientation and spatial frequency would show concurrent priming when *both* are relevant to the task at hand, one of them (orientation) is the target defining feature (or the "pop-out feature") while spatial frequency is the response defining feature. The task of the observer was thus to locate the *oddly oriented* item; whether the gabor patch was oriented to the left or right relative to vertical, and then respond whether the spatial frequency of the item was "high" or "low" (as defined in Fig. 2).

3.1. Methods

3.1.1. Observers

The same observers as in Experiment 1 participated. Thus two of the observers were again naïve about the pur-

pose of the experiment while one was the author. They all received rather extensive practice on the task (at least 300 trials, and until they were confident about performing the task).

3.1.2. Stimuli and procedure

The stimulus setup was essentially the same as in Experiment 1, except that this time the target defining feature was orientation so that all but one of the items on a particular trial was of one orientation while the target was of the other of the two possible orientations. This time the task was to indicate by keypress whether the target was of "high" or "low" spatial frequency (essentially only high or low relative to each other; the observers were shown examples of what counted as high or low spatial frequency on the task, before data collection started, see Section 2.1 for Experiment 1 and Fig. 2 for details). The observers were asked to indicate the spatial frequency of the target as fast as they could after the stimuli were presented. If the target was of high spatial frequency the correct response was to press the "8" key on the numeric keypad, while if the target was of low spatial frequency the correct response was "2". The color and spatial frequency of each item was determined randomly on each trial, but with the constraint that there were always four redscale and four greenscale gabors, and four each of high and low spatial frequency.

In other respects, the methods were similar to what was presented for Experiment 1.

3.2. Results

The response times for the three observers are shown in Fig. 5 as a function of how many times in a row a particular feature was repeated on the target (0, 1, 2 or 3 and more times). The results show that as the orientation of the target was repeated, response times became faster and also that with the repetition of spatial frequency, response times were speeded. Even more interestingly, there was also strong priming as the target *color* was repeated, even though color was irrelevant to the task. AK gave the incorrect response on 2.9% of the trials, GH on 2.1% and LSH on 1.5% of the trials, and these trials were not used for response time analyses.

The priming effects are summarised in Fig. 6, showing the average response times for each consecutive repetition; (the sum of no repetition minus 1 repetition; 1 repetition minus 2 repetitions and 2 minus 3 repetitions for each stimulus dimension, with this sum divided by three, as described for Experiment 1). The average priming effects show that priming was observed for all three features, albeit with some variation between individuals.

In sum, Experiment 2 shows that orientation and spatial frequency show concurrent priming—but in this case they
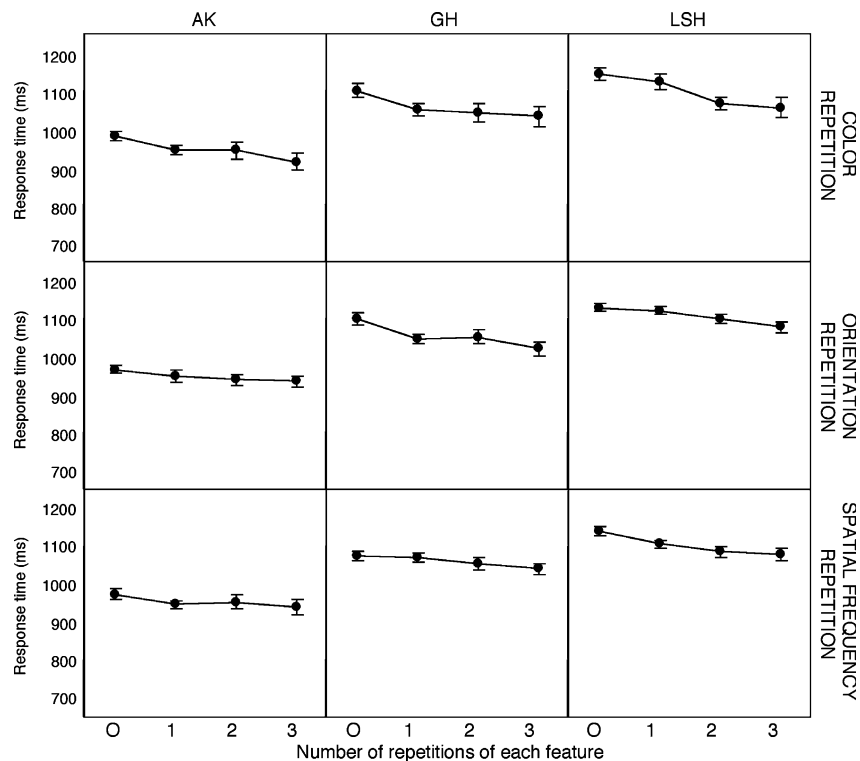

Fig. 5. Priming effects for the three types of repetition (color, orientation and spatial frequency) from Experiment 2. Response times are shown for each of the observers as a function of how many times in a row the feature in question was repeated (0, 1, 2 or 3 or more times in a row). The error bars show the standard error of the mean for each datapoint in the graphs.
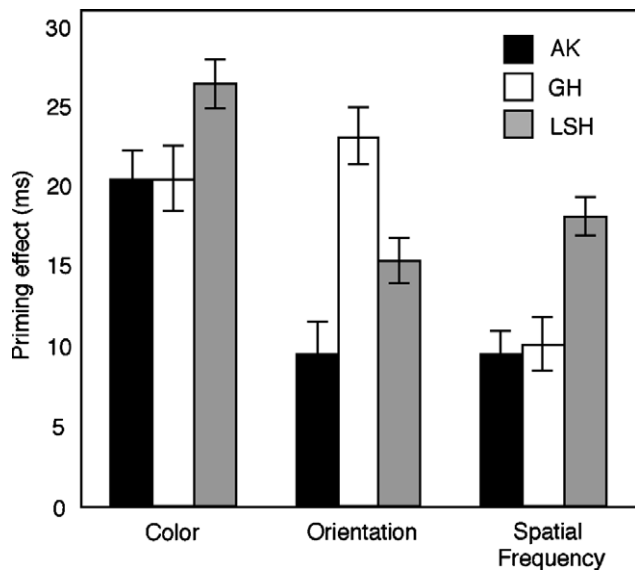
Fig. 6. Average priming effects for the three types of repetition (color, orientation and spatial frequency) from Experiment 2. The averages are obtained by taking the mean of three differences between performance as a function of feature repetition (the sum of no repetition minus 1 repetition; 1 repetition minus 2 repetitions and 2 minus 3 or more repetitions; with this sum divided by three). The error bars show the standard errors for these differences.

are both task relevant, but there was also considerable color priming showing that color priming can build up independently of spatial frequency and orientation priming, even when color is task irrelevant. Irrelevant features can lead to priming effects (as has been seen before, e.g., Maljkovic & Nakayama, 1996). The results also suggest that spatial frequency and orientation can show concurrent priming, but apparently both need to be task relevant for this to occur. The priming maximum for the features is thus seemingly larger when both are task relevant than when only one of them is task relevant. On the other hand, color priming can proceed unhindered even though it is task irrelevant.

Note that it is unlikely that the priming effect seen for both spatial frequency and orientation does not actually reflect concurrent priming, but instead that the pattern simply reflects that one or the other feature primed on each trial but not both features, but that the averaging spuriously indicates that both primed at the same time. The reason that this is unlikely is that the *total* amount of priming for spatial frequency and orientation should then be relatively similar for Experiments 1 and 2, whereas this is clearly not the case: for Experiment 1 the summed priming effect for spatial frequency and orientation was 11, 12 and 13 ms for the observers AK, GH and LSH respectively, whereas this summed priming effect for spatial frequency and orientation from Experiment 2 was 19, 33 and 32 ms for the same observers in the same order. The combined effect is thus larger for Experiment 2 and this difference is unlikely to be explained by the relatively modest differences between the absolute response times for the two experiments.

A more conclusive way to look at the same issue, however, is to look at response times on individual trials and investigate differences between trials where only one of the features is repeated versus when both are repeated. Looking at the mean response times on trials where both spatial frequency and orientation are repeated versus when only one is repeated, from Experiment 2, reveals that response times are faster on trials where both are repeated for all three observers, by 8 ms for AK, by 21 ms for GH and by 16 ms for observer LSH. This would clearly not be the case if priming on trials where both spatial frequency and orientation are repeated were due to the repetition of only one of the features on any particular trial.

4. Interim summary

To summarize the results so far, in the first experiment the critical pop-out feature was color, while the task feature was orientation. The "irrelevant" feature in the first experiment was spatial frequency. No priming was observed for the irrelevant feature in Experiment 1. In Experiment 2, however the irrelevant feature was color and somewhat surprisingly (at least in light of what was found in Experiment 1) there were strong priming effects attributable to the repetition of this target feature.

One possible reason is that color priming could proceed unhindered is that critical neural mechanisms involved in color processing do not show much overlap with the mechanisms involved in the processing of orientation or of spatial frequency. Furthermore, it is possible that the absence of priming for spatial frequency in the first experiment reflects that a priming maximum was reached for orientation and spatial frequency, but then once both the features are task relevant (as in Experiment 2) there is more potential for priming since the neural mechanisms devoted to their analysis are involved to a greater extent. There is, in fact, good reason to believe that orientation and spatial frequency are analysed by similar mechanisms, given what is known about the response properties of neurons in early visual areas of the cerebral cortices both with from evidence from single-cell neurophysiology (DeValois & DeValois, 1991; Hubel & Wiesel, 1962), as well as functional neuroimaging (Boynton, Demb, Glover, & Heeger, 1999; Haynes & Rees, 2005; Kamitani & Tong, 2005; Ress & Heeger, 2003; Tong, 2003). It is also noteworthy in this respect that priming effects were seen in early visual areas in the aforementioned neuroimaging study of priming in visual search (Kristjánsson et al., 2004), indicating that these priming effects may, to some degree, be related to neural activity at this early level in the visual processing stream. This issue is further addressed in Experiments 4 and 5 and the general discussion.

The results of Experiment 2 thus show that concurrent priming can occur for spatial frequency and orientation, showing that the two types of priming are not mutually

exclusive, but seemingly, both have to be task relevant. This may reflect that for features that share overlapping neural machinery, both need to be relevant to the task for concurrent priming of both features to occur.

5. Experiment 3—Target defining feature: Spatial frequency; response defining feature: Color

In the third experiment the priming of the three features of the gabor patches was contrasted further. This time the target defining feature was spatial frequency and the task was to indicate the color of the target with the odd spatial frequency. In other words, the task of the observers was to locate the item with the odd spatial frequency and report its color by keypress.

If it is true that for concurrent priming of both spatial frequency and orientation to occur, both need to be task relevant, as the previous two experiments suggest, there should be little or no priming for orientation since this time it is irrelevant to the task, while there should be intact priming for spatial frequency and color.

In pilot experiments it turned out that this task was more difficult than the task in the previous two experiments (possibly because the spatial frequency differences in the gabor patches are not as immediately salient as the orientation and color differences). To compensate for this, so that reaction times would be more comparable to the previous

experiments, the set size was reduced from 8 to 6 in an attempt to equate the difficulty of this task with the two previous ones, which resulted in faster responses.

5.1. Methods

The methodology was similar to what it was for the previous experiments, except that the set size was 6 for the reasons explained above, so that there were five distractors and one target on each trial. The target on each trial was the gabor patch with *the odd spatial frequency*. The task was to report by keypress the color of the target. If the target was red the correct response was to press the "4" key on the numeric keypad while if it was green the observers were to press "6". Red and green tape was placed on the "4" and "6" keys, respectively, to help observers perform the task. The color and orientation of each item was determined randomly on each trial, but with the constraint that there were always three red and three green gabor patches, and three gabors of each orientation. In other respects, the methods were similar to what has been described for the previous experiments.

5.2. Results

The response times as a function of the repetition of each of the features are shown in Fig. 7 for the three observers.
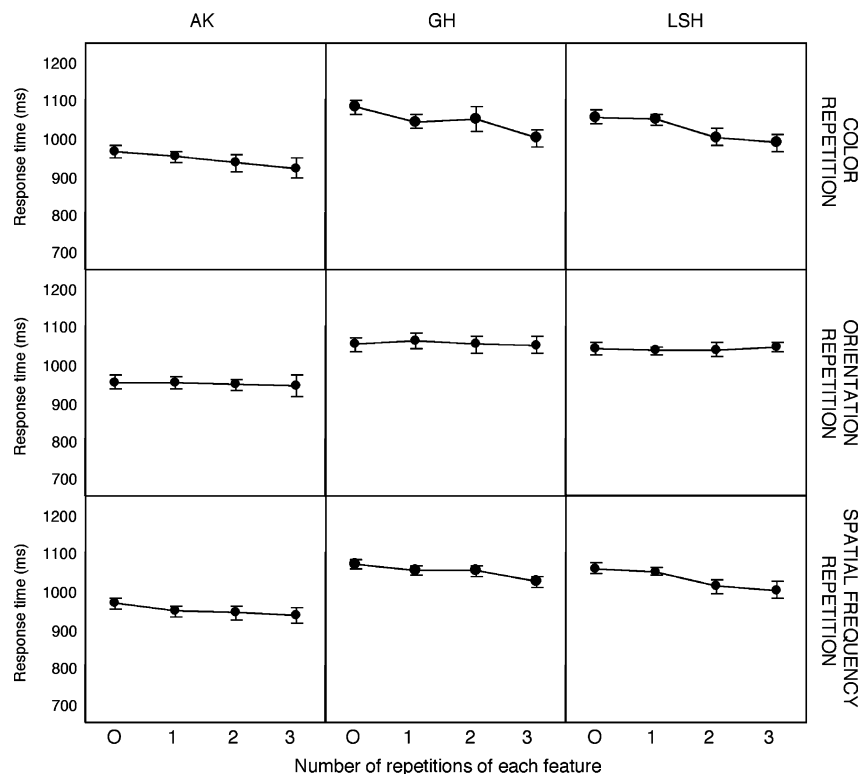

Fig. 7. Priming effects for the three types of repetition (color, orientation and spatial frequency) from Experiment 3. Response times are shown for each of the observers as a function of how many times in a row the feature in question was repeated (0, 1, 2 or 3 or more times in a row). The error bars show the standard deviations for each datapoint.
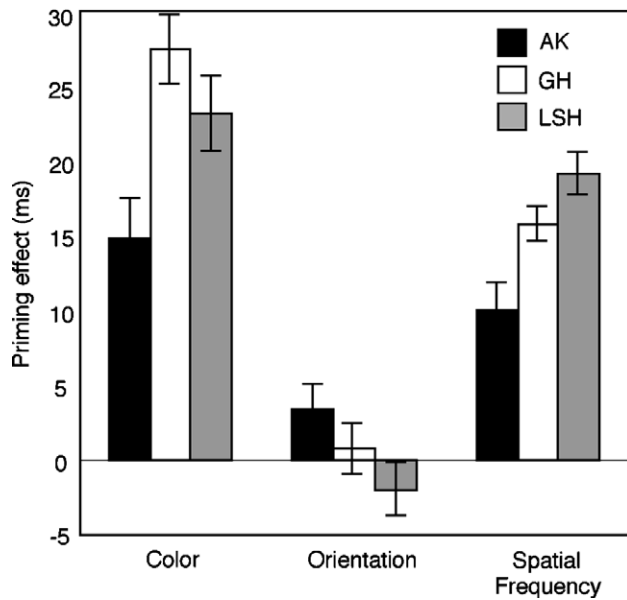
Fig. 8. Average priming effects for the three types of repetition (color, orientation and spatial frequency) from Experiment 3. The averages are obtained by taking the mean of three differences between performance as a function of feature repetition (taking the sum of no repetition minus 1 repetition; 1 repetition minus 2 repetitions and 2 minus 3 or more repetitions and then dividing this sum by three). The error bars show the standard error of the mean for this difference.

The magnitude of the priming effects is then shown in Fig. 8. In short the results were that there was strong color priming and considerable priming due to spatial frequency repetition. On the other hand, there was no evidence for the priming of orientation which was irrelevant to the task in this experiment. The results thus mimic the results of Experiment 1 where there was no priming of spatial frequency which was the task irrelevant feature in that experiment while priming was seen for orientation and color. Overall, the response times were similar to what they were in Experiment 2, but slightly longer than in Experiment 1, indicating that the difficulty of the task was similar to what it was in Experiment 2. AK responded incorrectly on 4.2% of the trials, GH on 2.9% and LSH on 2.3% of the trials.

In sum, the results from Experiment 3 constitute another indication that orientation priming and spatial frequency priming cannot co-occur unless both features are behaviorally important in some way and must thus be attended to. Priming of one annihilates the other, if one of the features is task irrelevant, but the results of Experiment 2 show that both orientation and spatial frequency repetition can lead to priming if both are relevant to the task. The results also suggest that color priming does not show any sort of interaction with spatial frequency and orientation priming since strong color priming is always observed but also that spatial frequency and orientation show a considerable interdependency in terms of the priming and that both need to be task relevant for priming of both to occur.

In light of the results from Experiments 1 and 3, one might ask whether spatial frequency and orientation show

priming when they are task irrelevant but there is no *competition* between the two. So far the results have simply shown that when one of the two is task relevant, that feature alone results in priming if it is repeated and that when both are task relevant priming is seen for both. One may ask what would happen if *both* are irrelevant to the task and only one varies and the other is kept constant. Will priming be seen for the feature dimension that is irrelevant but varies from trial to trial? This question was addressed in Experiments 4 and 5.

6. Experiment 4—Does orientation repetition lead to priming when it is task irrelevant but there is no competition from spatial frequency?

The results from the previous experiments show that priming of orientation and spatial frequency cannot co-occur when one of these features is task relevant and the other is task irrelevant. In a sense it seems that the two *compete* for finite resources in terms of repetition priming. In Experiment 4 this issue was further investigated by asking whether repetition of the orientation of the target will lead to a decrease in response times, even when orientation is irrelevant to the task, but there is no competition from spatial frequency since the spatial frequency of the gabors was kept constant and was completely irrelevant to the task. In other words, is it possible that the task relevance of orientation in Experiment 1 may have overwritten any priming from spatial frequency repetition and that the converse occurred in Experiment 3 where the roles of these two features was reversed?

In this experiment, the target defining feature was color, but to make spatial frequency irrelevant without adding a new stimulus dimension, a new task was needed. The observers thus performed a present/absent decision task. The task was to indicate whether an oddly colored target (red or green gabor patch) was present in an array of gabors of the other color. The orientation of the display items was decided randomly for each item in each array.

The critical question was whether there would be priming from a task irrelevant dimension like orientation—perhaps because competition with a related stimulus dimension (spatial frequency) is now absent since it is now not only task irrelevant but all the display items had the same spatial frequency. If it is true that having one task relevant feature of a similar sort (perhaps showing considerable overlap in the neural machinery required for its analysis) disrupts priming from the repetition of another similar feature, there might be priming for orientation even though this time around it is task irrelevant.

6.1. Methods

Methods were similar to what they were for previous experiments except that spatial frequency was kept constant at 3.1 cycles per degree of visual angle, and the task was a present/absent 2AFC task. The observers had to indicate

whether an oddly colored item (the target) was present among the distractors. The set size was 8 items. The target was either a redscale gabor among seven greenscale gabors or a greenscale gabor among seven redscale gabors. On 40% of the trials there was no target on the screen so that all eight gabors were of the same colorscale (redscale or greenscale). This ratio of blank versus target trials was used to maximize the number of target trials (without having too few absent trials so that the task would be compromised) since the critical manipulation was repetition of *target* features. The same equipment and stimulus values apply to this experiment as to the previously described experiments in the paper. Only the target present trials (with correct responses) were used for the analyses of response times. Furthermore, only trials where a target was present on the previous trial were used for the analyses of priming effects, since the critical manipulation was whether target features were the same or different from the ones on the preceding trial. The same three observers participated as in the previous experiments, and each underwent 3000 trials run in blocks of 100 trials each, preceded by at least 300 practice trials.

6.2. Results

Fig. 9 shows the response times as a function of target color repetition and target orientation repetition (0–3 or more repetitions). The results were that strong priming was found for repetition of both target color and orientation, even though orientation is task irrelevant this time. The priming effects for color were larger than for orientation for all observers, though (see Fig. 10), which is not surprising since only color was critical to the performance of the task. The absence of priming effects for orientation in Experiment 3 seems then to be due to interference from spatial frequency which was task relevant in that experiment. It is likely that priming had in some sense reached
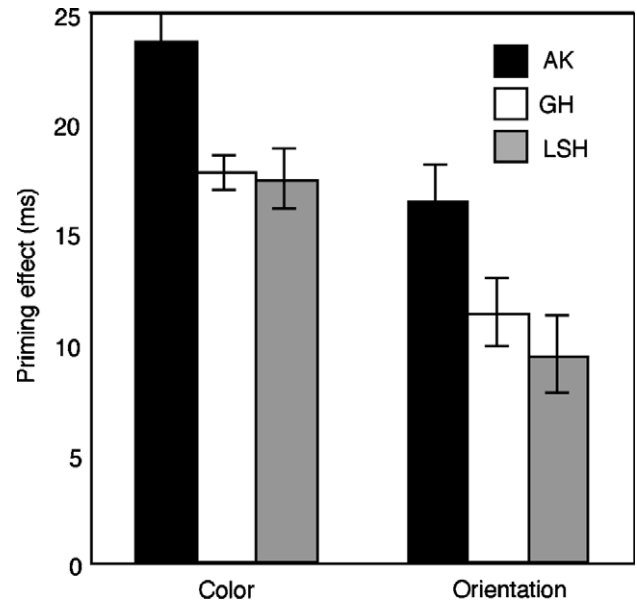

Fig. 10. The average priming effects for color and orientation from Experiment 4. The averages are obtained by taking the mean of three differences between performance as a function of feature repetition (taking the sum of no repetition minus 1 repetition; 1 repetition minus 2 repetitions and 2 minus 3 or more repetitions and then dividing that sum by three). The error bars show the standard errors for this difference for the observers.

capacity in that experiment with spatial frequency repetition. Recall however that Experiment 2 shows that priming can co-occur simultaneously for spatial frequency and orientation, but in that experiment *both* features were task relevant. AK made errors on 4.5% of the trials, GH on 4.1% and LSH on 3.3% of the trials.

The results suggest that a task relevant feature "vetoes" (in a functional sense) priming from an irrelevant dimension, that may share neural machinery to a notable extent
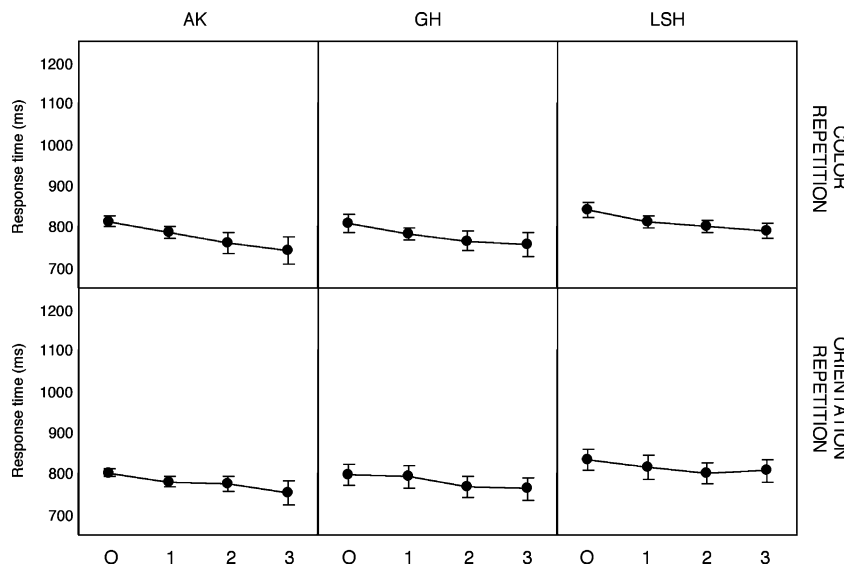

Fig. 9. The response times from Experiment 4 for the three observers (in the columns) as a function of 0, 1, 2 or 3 and more repetitions of target color (top row) and orientation (bottom row). The error bars show the standard errors of the mean for each datapoint.

with that feature, but also that such priming from an irrelevant dimension does occur when no such stimuli are task relevant. Note also that the results from Experiment 4 argue against the view that priming from orientation in Experiment 1 simply reflects the effects of response repetition since the priming seen is very similar to that study, but this time color is the response feature.

A critic might ask why no interference is seen from spatial frequency, since spatial frequency is not actually *absent* from the display, but simply does not vary. The answer most likely concerns exactly that, that spatial frequency is constant across the display and thus allows rapid rejection of all the items as irrelevant *as a group*. Wang et al. (2005) have argued that grouping plays a major role in efficient visual search in particular in grouping distractor items so that they can be rejected as non-targets *en masse* (see also Treisman, 1982). Another potential reason may be that the discrimination task used in the first three experiments may require more detailed analysis of the display items than the present/absent task used here, leading to more interference from the irrelevant dimension.

7. Experiment 5—Does spatial frequency repetition lead to priming effects when it is irrelevant but there is no competition from orientation?

Experiment 5 was essentially a repeat of Experiment 4 except that this time the irrelevant feature that was kept constant was orientation. The task of the observer was thus again to indicate whether an oddly colored item was present in the display. Each of the gabors in the search array was either of high or low spatial frequency (as defined in the Section 2.1 for Experiment 1). The orientation of each of the gabors was the same for all display items. The critical question was whether there would be priming attributable to the repetition of the spatial frequency of the target between trials even though it was task irrelevant.

7.1. Methods

Methods were similar to what they were for previous experiments except that orientation was kept constant (all the gabors were "vertical", or oriented zero degrees away from vertical), and the task was a present/absent 2AFC task. The observers had to indicate whether an oddly colored item (the target) was present among the distractors. The set size was 8 items. The target was either a redscale gabor among seven greenscale gabors or a greenscale gabor among seven redscale gabors. On 40% of the trials there was no target on the screen (for reasons explained for Experiment 4) so that all eight gabors were of the same colorscale (redscale or greenscale). Only the target present trials with correct responses were used for the analyses of priming effects, and only trials preceded by a target trial (as explained for Experiment 4). The same three observers participated as in the previous experiments, and each underwent 3000 trials run in blocks with 100 trials each, after at least 300 practice trials.

7.2. Results

Fig. 11 shows the response times as a function of target color repetition and target orientation repetition (0–3 or more repetitions). Strong priming was found for both color and spatial frequency, even though spatial frequency was task irrelevant. Again the color priming effect was quite a bit larger than the spatial frequency priming (see Fig. 12) presumably because color was the task determining feature in the experiment. The absence of priming effects for spatial frequency in Experiment 1 seems then to be due
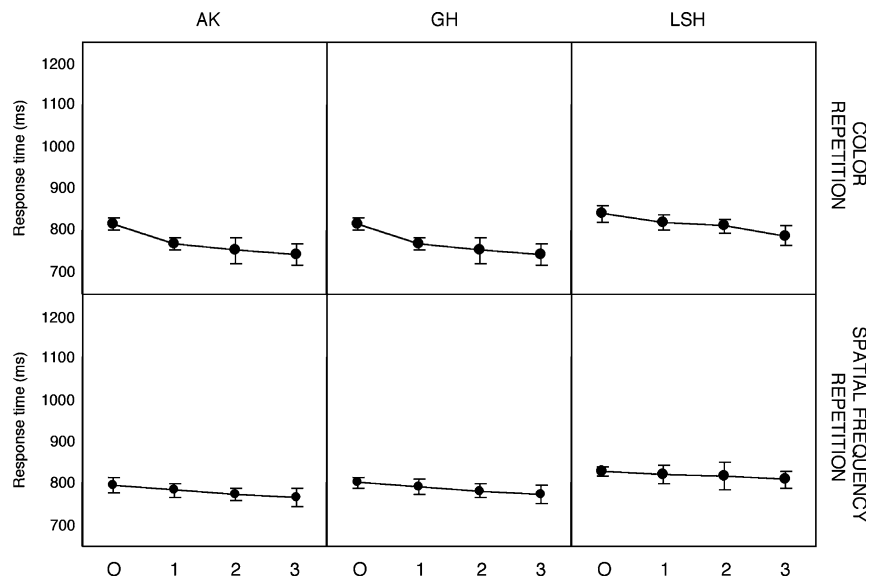

Fig. 11. The response times from Experiment 5 for the three observers (in the columns) as a function of 0, 1, 2 or 3 or more repetitions of target color (top row) and spatial frequency (bottom row). The error bars show the standard error of the mean for each datapoint.
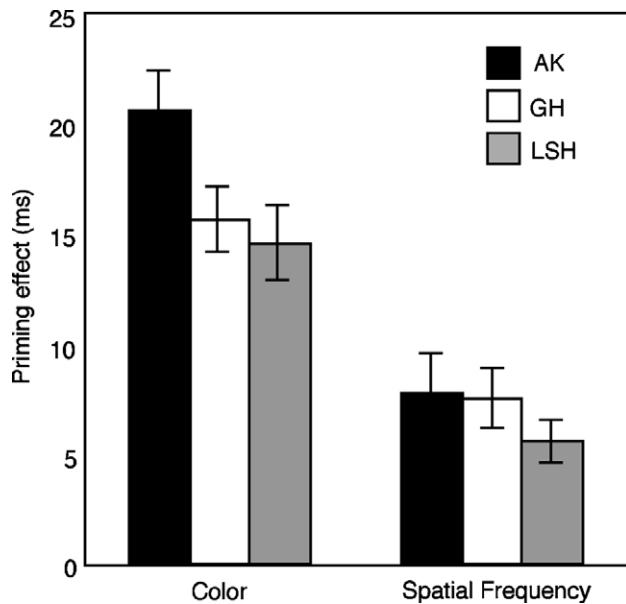
Fig. 12. The average priming effects for color and spatial frequency from Experiment 5. The averages are obtained by taking the mean of three differences between performance as a function of feature repetition (taking the sum of no repetition minus 1 repetition; 1 repetition minus 2 repetitions and 2 minus 3 or more repetitions and then dividing this sum by three). The error bars show the standard error of the mean for this difference.

to interference from orientation. The results are thus essentially a repeat of the results of Experiment 4 showing that repetition of the spatial frequency of the target can lead to considerable priming even when spatial frequency is task irrelevant, if there is no interference from orientation (which in this case did not vary, and was also task irrelevant). AK responded incorrectly on 5.3% of the trials, GH on 3.8% and LSH on 4.3% of the trials.

Again the results from this fifth experiment suggest that priming of an irrelevant feature can only occur when there is no interference from a task relevant feature that has similar, or overlapping properties. Again this absence of interference from orientation of the gabors (which was actually present in Experiment 3, where orientation was also task irrelevant) most likely reflects efficient grouping of iso-oriented gabors which can then be ignored en masse (as discussed for the case of spatial frequency in Experiment 4). Note also that the current present/absent task may not require as much scrutiny of the gabors as the discrimination task used in the first three experiments.

8. General discussion

What conclusions can be drawn about concurrent priming along multiple dimensions in light of the results in this paper? It seems that we are left with the somewhat puzzling conclusion that the answer to the question whether different stimulus dimensions show concurrent priming is: "it depends". It depends on whether the potential priming features are being attended to or not, or in other words

whether they are task relevant or not. If one is being attended to and the other one is not, priming is only seen for the attended dimension of the overlapping pair of features. As mentioned in the interim summary (Section 4) the results also open up some intriguing questions of whether features that are more likely to share neural machinery for their analysis are more likely to show interaction for their priming effects. To move this beyond the stage of pure speculation, however, would seem to require neuroimaging work, and the methods introduced in the current paper may in fact lend themselves well to such studies.

In all the experiments strong color priming was observed. There does not seem to be much interference from the other dimensions on the gabors on color priming. In contrast, spatial frequency and orientation seem to interact and interfere with each other in terms of repetition priming since only when both features were task relevant was priming seen for both (Experiment 2). And when spatial frequency and orientation were task relevant, priming was not seen for the other feature of the two if it was task irrelevant (Experiments 1 and 3). On the other hand, priming was seen for orientation (Experiment 4) and spatial frequency (Experiment 5) when they were task irrelevant but only when the other feature was also task irrelevant and stayed constant.

The results imply that there is a priming maximum, or a saturation point for priming effects. It is, in fact, not unreasonable to assume that such a priming maximum exists since such non-linearities abound in the visual system. There clearly must be a maximum of activity and priming is usually considered to be an altered activation state for certain features or objects (see e.g., Kristjánsson et al., 2002; Maljkovic & Nakayama, 1994), so one should, in fact, expect that residual activity from previous analysis of a similar feature would, in this sense, be capacity limited.

Magnussen and Greenlee (1999; see also Schachter, 1990, 1994) have argued for somewhat modular memory mechanisms for relatively basic level perceptual memory that relies on a set of parallel mechanisms for different stimulus features. The current results argue for some competition between dimensions. For example, if spatial frequency is the "pop-out" feature, there is no priming evident that can be attributed to repetition of target orientation whereas color priming is more or less intact. Neither of the other stimulus dimensions seem to interfere with color priming while they certainly interfere with one another. This may not be particularly surprising if one assumes that there is probably more overlap in the neural mechanisms for spatial frequency and orientation analysis while there is most likely much less neural overlap between color and spatial frequency and orientation. One need only look at the response properties of neurons in early visual areas that seem particularly responsive namely to spatial frequency (DeValois & DeValois, 1991) and orientation (Hubel & Wiesel, 1962), and the fact that different parts of the striate cortex seem to be involved in the analysis of color, on the one hand, spatial frequency and orientation on the other

(DeYoe & Van Essen, 1988; Livingstone & Hubel, 1987, 1988). But the results also suggest that task relevance plays a special role, and that capacity is determined to a certain extent by whether the potential priming features are task relevant or not.

8.1. Feature based priming versus "episodic retrieval"

Some have argued that priming in visual search tasks is based on whole objects rather than single features; the so-called "episodic retrieval" account. Huang et al. (2004) found that irrelevant features of objects lead to priming effects and thus assumed that priming occurs at the level of whole objects rather than at the level of single features as suggested, for example, by Maljkovic and Nakayama (1994, 1996). The evidence presented here, suggests otherwise however, or at least that the story is more complex than this, since here concurrent priming was seen for *some* independent dimensions of an object, but *not* for others. Thus priming was seen concurrently for orientation and color, but not for spatial frequency (Experiment 1), and for spatial frequency and color, but *not* for orientation (Experiment 3). Then priming was seen concurrently for all three features when both spatial frequency and orientation were relevant to the task at hand. This independent between-feature variation of priming effects would not be expected under the episodic retrieval account. If task relevance determines which features of an object result in priming, it seems much more likely that priming can occur at multiple different levels—at the level of single features *as well* as at the level of whole objects in some cases, which seems to be a rather straightforward interpretation of the results of Huang et al. (2004). Such a dual-stage conception of priming is in line with two stage accounts of visual short term memory suggested, for example, by Kristjánsson (in press; see also Wheeler and Treisman and Olson and Jiang, 2002 for somewhat related views) consisting of an early feature-based stage as well as a higher-level object based stage. Some evidence that this is indeed the way that the visual system works in terms of priming comes from Wig, Grafton, Demos, and Kelley (2005) who showed that selective disruption of frontal cortical activity (with transcranial magnetic stimulation) interfered with priming effects behaviorally, and at the neural level *except* in early visual areas which suggests that there is some dissociation between feature-based and conceptual-based priming. The results here suggest that such a distinction may also be found between feature-based and object-based priming.

8.2. A functional role for priming?

I have previously argued that priming plays a large role in visual perception, and in particular in the way attention is allocated over a given visual scene (Kristjánsson, 2006; see also Kristjánsson & Nakayama, 2003; Kristjánsson et al., 2002; Nakayama et al., 2004). Priming plays a large role in determining what we attend to at any given

moment. For example, the puzzles raised by the findings from the literature on change blindness (see e.g., Simons & Rensink, 2005 for a recent review) and inattentional blindness (see e.g., Mack & Rock, 1998; Most et al., 2001) have left people wondering what can account for the apparent stability of the visual world in light of how little information appears to be retained between successive glimpses of a given visual scene (see discussions in Ballard, Hayhoe, Pook, & Rao, 1997; O'Regan, 1992; O'Regan & Noe, 2001; Rensink, 2000). Human observers are severely insensitive to large disruptions to stimuli in our visual environment that we are not attending to. If we do not represent much of what appears in our visual field except at the moment that we attend to it—how do we reorient to previously attended items? My colleagues and I, have proposed that priming may be one mechanism that facilitates this (Kristjánsson, 2006; Nakayama et al., 2004; see also Kristjansson, Mackeben, & Nakayama, 2001; Kristjánsson & Nakayama, 2003). We tend to reorient our attention to those items in the visual field that are most like the ones that we have attended in the immediate past. Thus we can more easily track a behaviorally important item in our visual environment even though we look away from it momentarily. Note, however, that a seemingly contradictory evolutionary account has been proposed for the phenomenon of *inhibition of return* where it takes observers longer to shift their attention back to the locus of where they have just attended shortly after they attended there. (Posner & Cohen, 1984; Taylor & Klein, 1998). This has often been thought to reflect an evolved bias for novelty (see e.g., Klein, 2000). Note, however, that inhibition of return works over a few hundred milliseconds whereas priming typically occurs over a few seconds even up to 30 s by some estimates (see e.g., Maljkovic & Nakayama, 2000). Second, there is no inherent contradiction in proposing that the human visual system would have mechanisms both for biasing us to novelty when irrelevant items have been rejected as non-important as well as a mechanism that refocuses our attention quickly and efficiently back to behaviorally important items. In sum, the results in the current paper aid the understanding of how priming works, what role task relevance plays, as well as the importance of what is the main distinguishing feature of the target in determining the priming pattern.

8.3. The capacity of priming

In the literature there have been attempts at estimating between-feature and within-feature capacity of cognitive mechanisms. The most obvious example is the debate on capacity for visual short term memory (Alvarez & Cavanagh, 2004; Kristjánsson, in press; Luck & Vogel, 1997; Olson & Jiang, 2002; Wheeler & Treisman, 2002).

Estimates of the capacity for *priming* of different visual features have not been made previously to my knowledge. The current results indicate that the answer to that question will have to involve the overlap in the dimensions that

are being tapped. This is consistent with the findings from fMRI mentioned above indicating that priming related effects are seen in modularly specific areas (Kristjánsson et al., 2004). Future questions might involve testing the priming effects for e.g., objects that have two different values of the same feature dimension, for example, two colors.

Even though priming seems to be "at capacity" or " at maximum" in Experiments 1 and 3 in that repetition of the irrelevant feature does not lead to priming, the claim demands a caveat, since when both spatial frequency and orientation are task relevant as in Experiment 2, there seems to be an *increase* in the capacity for priming. The solution to this puzzle may be that when the neural mechanisms that are involved in the analysis of these two features are taxed to a larger extent, (since both features need to be attended to and analysed), the capacity for priming increases at the same time. This is a somewhat intriguing possibility, but it is in the end logical that greater activation would lead to greater priming (no activation presumably would not lead to any priming). When the neural mechanisms are involved to a greater extent, it is not unreasonable to assume that there is more potential for priming.

It is also quite clear from the current results that *task relevance* plays a key role in the priming pattern. That task relevance is important should not really come as a surprise given the demonstrated effects of attention upon activity of visual areas as measured in fMRI studies of changes in the BOLD signal (e.g., Heeger, Gandhi, Huk, & Boynton, 2001; Noesselt et al., 2002). But task relevance is clearly not the whole story since orientation and spatial frequency both result in repetition priming when they are irrelevant to the task (Experiments 4 and 5), but it seems to require no competition from the other feature.

9. Conclusions

It is clear that visual perception is an interpretative process. We do not passively register and represent the light that hits our retinas and nothing else (e.g., Attneave, 1954; Gibson, 1966; Hoffman, 1998; Rubin, 1921; see e.g., Kristjánsson, 2006 for a recent discussion). Previous viewing history plays a large role in what we subsequently see. Examples of this can be found, for example, in various aftereffects of viewing a particular type of stimulus, such as the motion aftereffect (Anstis, Verstraten, & Mather, 1998; Gibson, 1937; Kristjánsson, 2001) or the McCullough aftereffect (McCullough, 1965), on the perception of rivalrous stimuli (Leopold, Wilke, Maier, & Logothetis, 2002), as well as from priming, the topic of the current paper. The current study adds to our knowledge of such history effects. In particular, the results of the current experiments provide a few answers to the question of how simultaneous priming along multiple dimensions occurs, and what kind of circumstances are necessary for it to take place, but at the same time the results have uncovered some intriguing questions that demand attention in future experiments. The methods introduced here may lend themselves to future

neurophysiological and neuropsychological studies that may lead to some conclusions regarding what role overlap in neural mechanisms plays in the priming effects.

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