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Intertrial priming stemming from ambiguity: A new account of priming in visual search

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Sequential effects are ubiquitous in experimental psychology. Within visual search, performance is often speeded when participants search for the same target twice in a row, as opposed to two different targets. Here, we investigate such intertrial priming. Two experiments show that factors influencing search processes affect the presence and size of intertrial priming: It is larger when there are fewer elements in the visual display, and larger when there is a salient distractor present than when the target is the only salient element in the display. A control experiment showed that these increased priming effects were not due to longer baseline RTs. These findings, it is argued, are inconsistent with theories that explain intertrial priming as resulting from either only faster visual selection, or from episodic retrieval of responses. Instead, we propose that ambiguity in the stimulus or task underlies the occurrence of intertrial priming.

Sequential effects are ubiquitous in experimental psychology. People will react faster on a given trial when they repeat the same movement as on the previous trial (Bertelson, 1961; Goolsby & Suzuki, 2001; Soetens, 1998), when they perform the same task (Waszak, Hommel, & Allport, 2003), when they respond to a cue after the same time interval (Los, Knol, & Boers, 2001), when they see the same word or picture (Pecher & Raaijmakers, 1999; Warren & Morton, 1982), when they encounter a stimulus at the same location (Maljkovic & Nakayama, 1996), when they search for the same target stimulus (Maljkovic & Nakayama, 1994; Müller, Heller, & Ziegler, 1995), or search for a different target but in the same distractor configuration (Chun & Jiang, 1998).

Within visual search, reaction time (RT) benefits have been observed when the same target has to be found on two successive trials (Hillstrom, 2000; Huang, Holcombe, & Pashler, 2004; Maljkovic & Nakayama, 1994, 2000; Müller et al., 1995; Olivers & Humphreys, 2003). Maljkovic and Nakayama

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(1994) were the first to show that these benefits occur even for targets that, in their words, ''pop out'' of the display. In their experiments, target diamonds could be green among red diamonds, or red among green diamonds. If the target had the same colour on two consecutive trials, observers were some 60–100 ms faster than when the target colour switched. This ''priming of pop-out'' phenomenon (POP), as the authors called it, has been shown to be relatively short-living (as a 90 s interval between consecutive trials negated it; Maljkovic & Nakayama, 2000), but it is nevertheless a robust phenomenon (Found & Müller, 1996; Goolsby & Suzuki, 2001; Kumada, 2001; McPeek, Maljkovic, & Nakayama, 1999; Müller, Reimann, & Krummenacher, 2003). Similar intertrial priming effects have also been found for targets that do not pop out (Hillstrom, 2000; Kristjánsson, Wang, & Nakayama, 2002).

Most researchers agree that intertrial priming reflects automatic, implicit mechanisms. For instance, Maljkovic and Nakayama (1994; see also Hillstrom, 2000; Olivers & Humphreys, 2003) showed that the intertrial priming effects can go back as far as eight trials. It is unlikely that observers consciously base their search strategy on these distant trials. Indeed, Maljkovic and Nakayama (2000) have shown that observers hardly remember what they saw on the immediately preceding trial. In another experiment of Maljkovic and Nakayama (1994), observers could explicitly expect a switch trial (because they alternated regularly with same trials). This did not eliminate the costs associated with switch trials, indicating that intertrial priming effects could not be overcome by top-down settings. Other convincing evidence comes from a study of Theeuwes, Reimann, and Mortier (in press). They used cues showing one of two possible target shapes. However, each shape cue predicted with 80% validity that the *other* shape would be the target. Nevertheless responses were faster in the 20% of trials in which a cue was followed by itself as target. This suggests that the cue led to bottom-up, automatic priming, and that such priming is difficult to influence by top-down expectancy.

Apart from the implicit nature of the effect, there is little consensus on what causes intertrial priming. One group of accounts, which we will collectively refer to as the *visual selection* view, stresses the perceptual and attentional nature of the priming effect. Maljkovic and Nakayama (2000, p. 592) propose an ''implicit yet primitive system [that] can facilitate the return to recently attended targets and locations'', and ''ensure that objects of recent interest would be repeatedly sampled''. According to Müller and colleagues (Found & Müller, 1996; Müller et al., 1995), visual selection is modulated by dimension-specific salience signals. If a target in trial t is defined by a feature on one dimension (e.g., colour), its associated attentional weight will increase at the expense of other dimensions (e.g., orientation). This will make subsequent targets that pop out on that dimension easier to detect, leading to a priming effect. Evidence from single-cell recordings in monkeys is consistent with the general idea that a target can become more salient through intertrial priming. When monkeys make

eye movements to a colour singleton, neural responses in the frontal eye fields to the singleton are larger when its colour remains the same as in the previous trial, than when target colour is changed (Bichot & Schall, 2002). In the same vein, neural responses to distractors are attenuated when the distractor colour remains constant, relative to when it changes. These effects are not very large, but they do suggest that a repeated target colour in an odd-one-out search task becomes more salient, and a distractor colour less so.

Recently, however, several theories have taken a different tack, mostly because of evidence that repetition of features is not invariably beneficial. We will refer to this group of theories as the *response selection* view, as they place priming within the process of response selection. For instance, Cohen and Magen (1999) suggest, on the basis of the response selection model of Cohen and Shoup (1997), that intertrial priming in visual search results from the activation of a response. If a stimulus is consistently mapped onto one response, its occurrence on previous trials will prime that response, leading to a shorter RT. If the stimulus is not consistently mapped to one response, intertrial priming is thought not to occur. One version of such a *response selection* view, stemming from the task switching literature, suggests that intertrial benefits result mostly from retrieval of task-relevant episodic memories (Logan, 2002; Neill, 1997; Waszak et al., 2003). This episodic retrieval account assumes that the translation from stimulus to response does not occur automatically, but is an effortful process. During that process, memories of previous occurrences involving similar stimuli are automatically retrieved. This also means retrieving the response then given. If the retrieved response matches the one that is now needed, the response is speeded. When the retrieved response does not match the one commensurate with the current stimulus, the response is slowed.

Response selection views can explain data such as those of Huang at et al. (2004). These authors used a search task in which targets always had a size that differed from all other elements in the display: They could either be smaller or larger than nontargets. They showed that a repetition of target size was most beneficial when the required response was the same as that on the previous trial, and less so when it changed. In the response selection view, if the current target has the same size as the previous target, but a different response associated with it, retrieving a representation of the previous trial will not benefit performance on the current one.

Neither the visual selection view nor the response selection view wholly accounts for the extant data. A pure visual selection view on priming is difficult to reconcile with evidence that intertrial priming depends on the responses required of the participants. For instance, Kumada (2001) found intertrial priming in a search task when participants determined the presence or absence of the target (a *present/absent* task), but no priming in a so-called *compound* search task, in which participants were presented with the very same stimuli, but where the target was always present and responses were to a small arrow presented

inside it. Since the stimuli had remained identical and only the required response had changed, Kumada concluded that intertrial priming is response specific.

A response selection view, on the other hand, is difficult to reconcile with the pervasiveness of intertrial priming in visual search. Many experiments have shown robust priming effects even in compound search tasks, in which a response selection view would not expect them (since the response feature is decoupled from the target feature). Most prominently, Maljkovic and Nakayama (1994) found intertrial priming with a compound task, as did other researchers (Goolsby & Suzuki, 2001; Hillstrom, 2000; Olivers & Humphreys, 2003; Pinto, Olivers, & Theeuwes, in press). Another finding that is difficult to reconcile with the response selection view is that intertrial priming in the Maljkovic and Nakayama (1994) type of displays does not occur when participants do not have to search for the target, for example because a cue shows where the target will appear, or because the target is the only element in the display (Goolsby & Suzuki, 2001). Since the response requirements do not change with the elimination of visual search, a response selection view would not predict that intertrial priming disappears in these cases.

The evidence to date thus suggests that intertrial priming in visual search is not something occurring only in visual selection, or only at response selection. Neither view offers a comprehensive explanation for when intertrial priming occurs, or when it does not. In the present paper, we seek to provide and test a new account that we believe more comprehensively explains the presence or absence of intertrial priming in visual search.

Before we introduce this account it is instructive to take a closer look at the studies that did find intertrial priming in a compound task setting (that is, when the responses were decoupled from the search). What characterizes all these studies is a certain degree of ambiguity in the stimulus displays. For instance, in Olivers and Humphreys' (2003) study, the target was not always the only item in the display carrying a unique feature: On a considerable proportion of trials there was also a so-called singleton distractor present that interfered with search as indicated by longer RTs. Similarly, Pinto et al. (in press) found strong intertrial priming effects when the search displays contained a singleton distractor, whereas priming was much reduced or even absent when there was no distractor. Neither did the target contain a unique feature in the crucial experiments of Hillstrom's (2000) study. She used displays in which the target had to be distinguished from either a singleton distractor or from multiple sets of distractors each of which it shared a feature with (so called conjunction search). Finally, in Maljkovic and Nakayama's (1994) original study, the target was unique, but relative to only two distractors. That is, the target was either a red diamond between two green diamonds, or vice versa, a green diamond between two red diamonds. We suggest that this relatively small distractor/target ratio induced a degree of ambiguity as to which of the items was the target.

Based on these observations, we propose that intertrial priming may occur at any processing step, from attentional selection to response execution, but only under specific circumstances. In particular, we propose that an important factor determining whether or not intertrial priming occurs in visual search tasks is the ambiguity of the task, independent of in which stadium that ambiguity plays out. If it is ambiguous what the target is, visual selection will rely relatively more on what was selected in previous trials. If it is ambiguous what the response should be, response selection will rely more heavily on what response was coupled with a stimulus on previous trials. Elsewhere, we argue that ambiguity is stronger in present-absent tasks than in compound search tasks (Olivers & Meeter, in press), and that therefore intertrial priming is more easily found in the former than in the latter task. Here, we propose that in the visual selection stage, a display is ambiguous when multiple elements are plausible targets for visual selection, and thus are in competition with one another. It is in those cases that the heightened salience of a repeated target can make a difference. If, on the other hand, there is little competition in the visual display, the increased salience of a target will not increase the already high likelihood that the target will be selected, and will therefore not lead to intertrial priming. We thus propose that it is not the absolute salience of the target that determines whether intertrial priming occurs, but whether it is unambiguously the most salient element in the display.

The difference between our account and the visual selection view is that target selection does not always lead to priming of its features, but only under ambiguous circumstances. The difference between our account and the response selection view is that the trace of activation does not lead all the way from stimulus to response but is specific to the level at which the ambiguity occurs.

At what level does the competition for visual selection occur? We propose that it is initially at a level where salience is computed in a strictly bottom-up fashion, such as in a salience map of the kind featuring in some models of attention (e.g., Navalpakkam & Itti, 2005). In other models top-down target settings help determine the salience of visual objects (e.g., Bundesen, Habekost, & Kyllingsbaek, 2005; Muller et al., 1995; Wolfe, Butcher, Lee, & Hyle, 2003), but as argued above the presence of top-down settings do not seem to influence the occurrence of intertrial priming (Maljkovic & Nakayama, 1994; Theeuwes et al., in press).[1] Moreover, strictly bottom-up competition underlying priming would help explain why cueing the identity of the upcoming target does not eliminate intertrial priming (Hillstrom, 2000; Müller et al., 2003). Note that this does not mean that the intertrial priming is due to bottom-up signals alone. It is possible (and even likely) that the initial ambiguity needs to be resolved with the aid of top-down signals (e.g., the rejection of a nontarget). These signals will

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[1] Intertrial priming itself has been identified as a top-down influence on visual search by some authors. We would argue, however, that the lack of strategic control on priming effects would qualify it as a bottom-up effect.

then automatically carry over to the subsequent trial. Our claim is that intertrial priming is large in search tasks in which bottom-up models of the salience map predict competition for visual selection (which needs to be resolved), and small in search tasks in which there is less competition (and hence less need for ambiguity resolution).

An important factor that increases competition for selection in bottom-up models of salience is distractor heterogeneity. Our account would thus predict that heterogeneity increases intertrial priming. Indeed, intertrial priming is found when a singleton distractor competes with the target for selection (Olivers & Humphreys, 2003; Pinto et al., in press), when distractors are so few in number that they do not effectively inhibit one another (Maljkovic & Nakayama, 1994), or when the target must be selected from a heterogeneous set of distractors (Hillstrom, 2000). In contrast, the search displays that failed to yield intertrial priming (e.g., Kumada, 2001) involved unambiguous unique targets against a background of many homogenous distractors.

In the present study, we hope to show that ambiguity in target identity, in the form of competition, may underlie priming in the visual selection stage in compound tasks. Two experiments will show that factors influencing competition for visual selection affect the size of intertrial priming, while a control experiment (Experiment 2) will show that absolute salience per se is not a determinant of intertrial priming.

EXPERIMENT 1:
SET SIZE AFFECTS INTERTRIAL PRIMING

Although some compound search tasks did not yield any (e.g., Kumada, 2001), the compound search task employed by Maljkovic and Nakayama (1994, 2000) yielded reliable intertrial priming effects. One salient difference between their task and those used by others is the number of elements in the display. Whereas in typical compound search tasks the target is surrounded by many distractor elements, the target in Maljkovic and Nakayama's studies was accompanied by just two distractors that were widely spaced across the display. It is known that in such tasks pop-out may be stronger when there are many distractor elements in the display, than when there are few (Bravo & Nakayama, 1992). The more distractors there are, the more unique and more salient the target becomes relative to these distractors, reducing competition. Our hypothesis would thus predict that as the number of distractor elements increases, and the ambiguity is reduced, intertrial priming effects will also be reduced. This will be investigated in Experiment 1, in which the number of elements in the display will be varied.

Another difference between the study of Maljkovic and Nakayama (1994) and others investigating compound search is the task employed. Most compound search tasks require participants to identify some symbol within the target

element (e.g., Kumada, 2001; Theeuwes, 1992), whereas Maljkovic and Nakayama (1994) required participants to detect which corner of a target diamond was cut off. Although we did not expect this difference to affect intertrial priming, we also compared the task employed by Maljkovic and Nakayama (1994) with a more typical symbol identification task.

Methods

Participants.   Eight observers participated in the experiment for a small monetary compensation (4 men, 4 women, mean age 23). All had normal or corrected-to-normal eyesight, and normal colour vision.

Stimuli.   Participants were seated in a dimly lit room, at a distance of approximately 70 cm from a 21-inch monitor. Stimuli were adapted from Maljkovic and Nakayama (1994). Search screens contained three or twelve diamonds, one of which was red (CIE x,y chromaticity coordinates 0.597, 0.366, 9.51 cd/m^2) while all the others were green (CIE 0.254, 0.649, 12.13 cd/m^2), or vice versa. Stimuli appeared against a black background at either a random three of twelve equidistant locations, or at all twelve locations, arranged on an imaginary ellipse of, horizontally, 10 degrees of visual angle, and vertically, 8 degrees of visual angle. Diamonds were 1.1 * 1.1 degrees of visual angle. On trials in which the task was to detect which corner of a target diamond was cut off, all diamonds had 0.14 degrees cut off on either the left or the right side (see Figure 1). On trials in which the task was to identify a symbol inside the diamonds, each diamond had in it either a left-pointing arrowhead (''<'') or a right-pointing arrowhead (''>''). The response was chosen randomly at each trial.

Procedure.   Participants were instructed that they would see a number of diamonds, one with an odd colour, and that they had to identify either the corner cut off the odd-coloured diamond, or the arrowhead inside it. They were required to respond to targets with a leftward arrowhead or left cut-off with the ''Z'' key, and to targets with a rightward arrowhead or right cut-off with the ''M'' key.

Trials were organized in eight blocks of 80 trials, preceded by four blocks of 8 practice trials. For each task (arrowheads and corners) two blocks were run with 3 elements per search screen, and two with 12 elements. Each of the four practice blocks used a different task and element number combination. Order of the practice and experimental blocks was randomized (experimental blocks with the same task and element number combination were always run after another). Each block contained 40 switch trials, and 40 trials in which the target colour was repeated. Target colour was random at the start of each block, and then changed as a function of repetition/switch trials. Trials began with a 500 ms
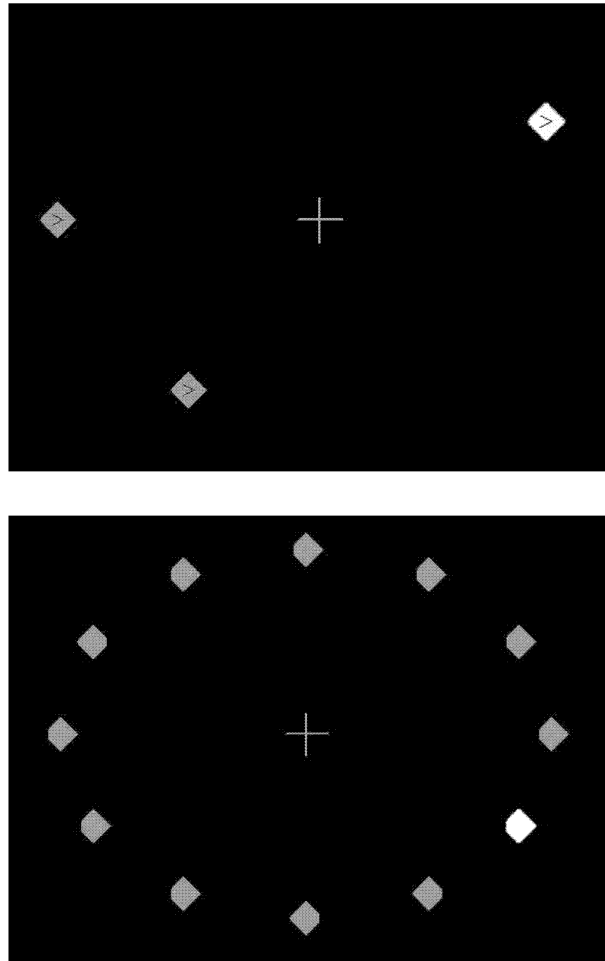
Figure 1.   Example of search displays in Experiment 1. Upper panel: Symbols task with 3 elements; bottom panel: Corners task with 12 elements (in both only the central part of the screen shown).

presentation of a fixation cross. Then the search display was presented until the observer responded. Observers were notified when they had made an error, and given feedback after each block.

Results and discussion

Trials longer than 1500 ms, around 3% of the total, were not analysed. On average, observers made 6.1% errors, which were excluded from our RT analyses. We performed an ANOVA to determine whether task variables had

effects on error rates (see Table 1). None of the main effects was significant, nor were any interactions.

On RT, the corners task proved a little easier than the arrowheads task, $F(1, 7)$ = 29.88, p = .001, MSE = 1256.6 (Figure 2). A larger effect was found for the number of elements: Locating the target proved easier with twelve elements than with three elements, $F(1, 7)$ = 54.74, $p < .001$, MSE = 2284.2. Trials in which target colour was repeated had shorter latencies than those in which target colour was changed, $F(1, 7)$ = 39.56, $p < .001$, MSE = 1236.4. There was no interaction between the number of elements and the task (corners vs. arrows), $F(1, 7)$ = 1.48, p = .262, MSE = 2809.9, nor were repetition effects dependent on task ($F <$ 1), nor was there a three-way interaction ($F < 1$). However, and most impor-

TABLE 1
Mean error proportions in Experiments 1, 2, and 3, for trials on which the target was the same as on the previous trial, and on which it was changed from the previous trial

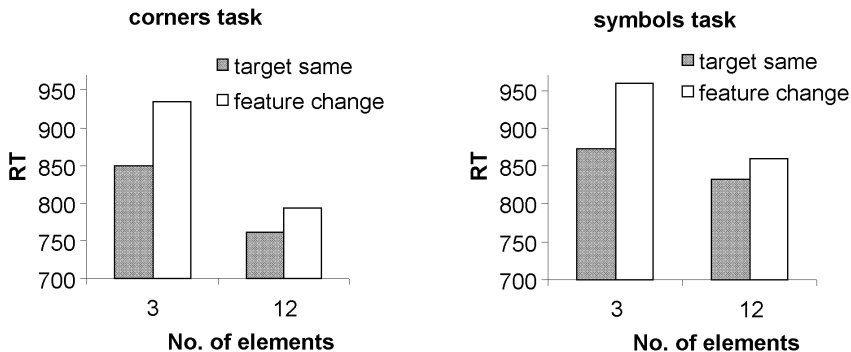|	Target same	Feature change
Exp. 1		
3 elements	.07	.07
12 elements	.07	.07
Exp. 2		
Large elements	.05	.05
Small elements	.06	.07
Exp. 3		
No distractor	.03	.04
Distractor	.04	.04

Figure 2.   Mean RT in Experiment 1, as a function of the number of elements, whether or not the target colour was repeated or changed from the previous trial, and the task employed.

tantly, repetition effects were larger when there were 3 elements than when there were 12 elements (85 ms vs. 30 ms, see Figure 2), $F(1, 7) = 12.87$, $p = .009$, $MSE = 1006.1$. Repetition effects were still significant for the 12 element condition, though, $t(7) = 3.73$, $p = .007$.

We also performed an analysis in which response repetition was taken in as a factor (i.e., whether or not the same response was elicited on two successive trials), collapsing over task (Table 2). There was a trend toward an effect of response repetition, $F(1, 7) = 3.64$, $p = .098$, $MSE = 143.0$, but there were no interactions of this factor with the number of elements, $F(1, 7) = 3.10$, $p = .121$, $MSE = 212.3$, or with target repetition ($F < 1$), nor was there a three-way interaction ($F < 1$).

We found that the type of compound task performed by the observers (responding to corners or arrowheads) did not influence the size of intertrial priming, but that the number of nontarget elements did (repetition benefits were 85 ms when there were 3 elements in the search display, and only 30 ms for the 12 element displays). Experiment 1 thus shows that reducing competition for visual selection can influence the strength of intertrial effects. This seems incompatible with the response selection view. The number of elements in the display does not change in any way the stimulus–response mappings, and thus should also not change the effect of retrieving stimulus–response mappings. Instead, the results are in line with our hypothesis that ambiguity drives intertrial priming: With three elements, the target is not necessarily more distinctive than distractors, while with twelve elements, the target clearly pops out of the display.

One confounding factor is that in the condition in which intertrial priming effects were larger, RTs were also higher. It is possible that higher base RT lead to stronger intertrial priming, for example if the effects of priming build up during the time that a display is searched. As a first way to address this alternative explanation, we computed the first to fourth quintile in each condition

TABLE 2

Mean RT in Experiments 1 and 3, for trials on which the response was the same or changed relative to the previous trial, and on which the target was the same or changed from the previous trial

	Response same		Response change	
	Target same	*Feature change*	*Target same*	*Feature change*
Exp. 1				
3 elements	843	927	842	927
12 elements	771	808	792	812
Exp. 3				
No distractor	705	706	698	703
Distractor	788	818	773	832
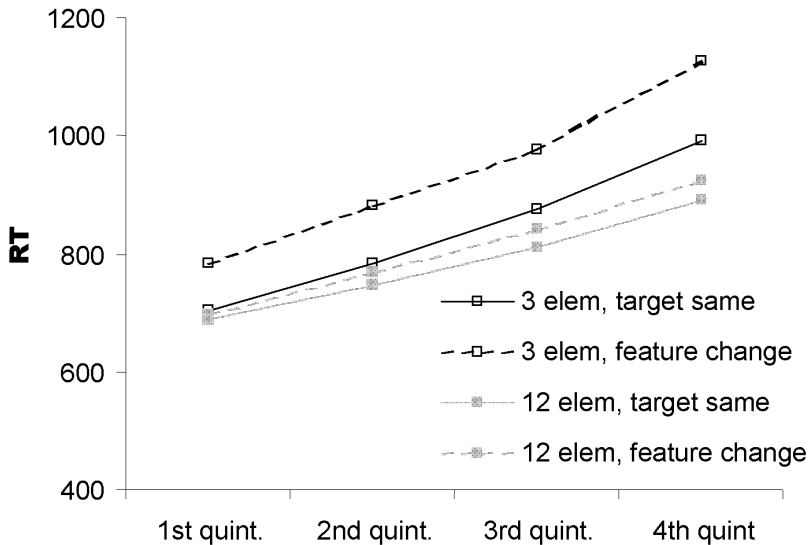
Figure 3.   First, second, and third quartile for the conditions with 3 and 12 elements in Experiment 1, and for trials in which the target colour was repeated vs. where it was changed.

(see Figure 3). Priming effects seemed broadly equal in size for the whole RT distribution. An ANOVA comparing priming effects for the first versus for the fourth quintile found only a trend towards a greater priming effect at longer RTs: Interaction between target repetition and quintile, $F(1, 7) = 4.17$, $p = .077$, $MSE = 1400.2$. There was not even a trend when priming effects were compared for the second and fourth quintile, $F(1, 7) = 2.66$, $p > .1$, $MSE = 795.6$. It is thus unlikely that higher RTs can explain the bulk of the increased priming effects in the three elements condition as compared to the twelve elements condition.

EXPERIMENT 2: EFFECT OF LONGER LATENCIES

Although the quintiles analysis provides a first indication that longer RTs are not the determining factor for priming effects, we performed a control experiment in which we varied reaction time, without changing ambiguity. For this purpose we repeated the crucial conditions of Experiment 1, but in addition manipulated the size of the elements in the search display. Smaller elements were expected to lead to longer RTs, without directly affecting the ambiguity of the target–distractor relationship.

Methods

Participants.   Ten observers participated in the experiment for a small monetary compensation (6 men, 4 women, mean age 23). All had normal or corrected-to-normal eyesight, and normal colour vision (self-reported).

Stimuli and procedure. Displays were similar to those used in the arrowhead condition of Experiment 1, except for the size of the diamonds. These were either smaller or larger (0.72 * 0.72 or 2.2 * 2.2 degrees of visual angle) than those used in Experiment 1. We varied the number of diamonds as in Experiment 1 (3 vs. 12), and used the same two colours. Participants were instructed that they would see a number of diamonds, and that the target diamond would have a unique colour. Their task was again to identify the arrowhead inside the target diamond, and to respond with either the ''Z'' key (''<'') or the ''M'' key (''>'').

Observers were given 32 practice trials, organized in 8-trial blocks with large or small diamonds. They then went through four blocks, in randomized order, of 160 trials. In each block one combination of size (large or small) and number (3 or 12) of elements were used. Again feedback was given every 80 trials, and observers were immediately notified when they had made an error.

Results and discussion

Trials longer than 1500 ms, about 1.5% of the total, were not analysed. On average, observers made 6.0% errors (Table 1), which were excluded from our RT analyses. ANOVAs did not reveal effects of any variable on error rates.
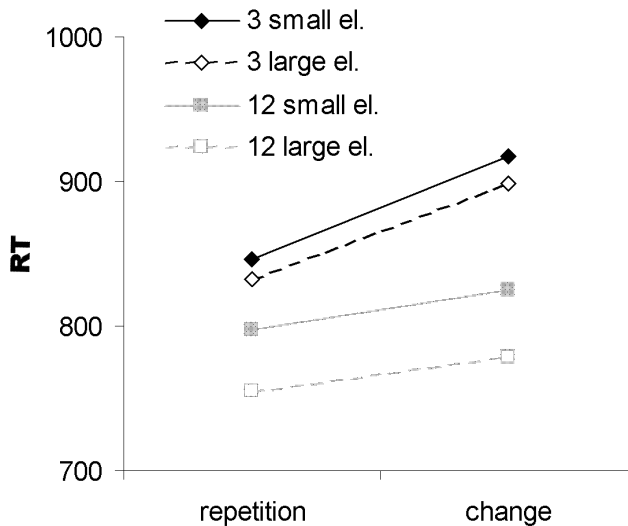
Figure 4.   Mean RT in Experiment 2 as a function of the number of elements in the display, their size (small or large), and of whether the target colour was repeated or changed from the previous trial.

The mean RTs are plotted in Figure 4. As in Experiment 1, search was slower in the condition with 3 diamonds than in the condition with 12 diamonds, $F(1, 9)$ = 29.85, $p < .001$, MSE = 4736.1, and was faster when a target was repeated than when it was changed, $F(1, 9)$ = 61.17, $p < .001$, MSE = 758.2. Diamond size also affected search, with longer RTs for small than for large diamonds, $F(1, 9)$ = 6.18, p = .035, MSE = 4713.4. The number of elements affected intertrial priming effects: as in Experiment 1, priming was larger in 3 diamond conditions (mean 68.6 ms) than in 12 diamond conditions (mean 25.5 ms), $F(1, 9)$ = 22.29, p = .001, MSE = 563.2. However, element size did not interact with target colour repetition, $F(1, 9) < 1$. There was no interaction between size and element number, $F(1, 9)$ = 2.03, p = .19, MSE = 1695.8, and no three-way interaction ($F < 1$). Experiment 2 thus shows that a factor that slows search does not necessarily increase the size of intertrial priming, which falsifies the alternative account of the results of Experiment 1 that baseline RT differences, instead of ambiguity, explain the effects of element number on intertrial priming.

EXPERIMENT 3: A SINGLETON DISTRACTOR AFFECTS INTERTRIAL PRIMING

The results of Experiments 1 and 2 suggest that ambiguity in target identity is indeed a factor associated with the occurrence of intertrial priming effects. In those experiments, ambiguity was related to the number of distractors in the display, with smaller numbers leading to increased competition. In Experiment 3 we manipulated competition directly by introducing a singleton distractor, which, like the target, carried a unique colour. Both target and singleton distractor were highly salient, increasing competition for visual selection, and thus ambiguity. We should thus find increased priming effects in this condition compared to a control condition in which no such singleton distractor is present.

Methods

Participants. Six observers participated in the experiment for a small monetary compensation (4 men, 2 women, mean age 21). All had normal or corrected-to-normal eyesight, and normal colour vision (self-reported).

Stimuli and procedure. Displays were similar to those used in the 12-element arrowhead condition of Experiment 1, except for the colour of the nontarget diamonds. These were either all 11 grey (no distractor condition), or consisted of 10 grey nontargets and 1 blue or yellow singleton distractor (blue CIE x,y chromaticity coordinates 0.165, 0.154, 11.59 cd/m^2; and yellow, CIE 0.398, 0.527, 37.34 cd/m^2). The colour of the target diamond varied unpredictably from green to red, as did the singleton distractor colour (from blue to yellow) in the blocks with colour distractors. Each diamond contained

either a leftward or a rightward arrowhead. Participants were instructed that they would see a number of diamonds, that the target diamond would be either green or red, and that nontarget diamonds would be grey, yellow or blue. Again their task was to identify the arrowhead inside the target diamond, responding with the ''Z'' (''<'') or ''M'' keys (''>'').

Observers were given 64 practice trials, organized in 16-trial blocks with or without singleton distractor. They then went through two blocks, in counter-balanced order, of which one contained 240 trials with a singleton distractor, the other 240 trials without a singleton distractor, with feedback given every 80 trials as in the previous experiments (observers were again immediately notified when they had made an error).

Results and discussion

Trials longer than 1500 ms, less than 1% of the total, were not analysed. On average, observers made 3.4% errors (Table 1), which were excluded from our RT analyses. ANOVAs did not reveal effects of any variable on error rates.

Search was slower for trials with a singleton distractor than for those without one, $F(1, 5) = 49.94$, $p = .001$, $MSE = 1171.6$ (see Figure 5), and was faster when a target was repeated than when it was changed, $F(1, 5) = 10.78$, $p = .022$, $MSE = 266.2$. The singleton distractor also affected intertrial priming effects: Priming was larger when a distractor was present than when it was not, $F(1, 5) = 10.80$, $p = .022$, $MSE = 230.7$. In fact, there was no effect of target colour repetition in the no-distractor condition, $t(5) < 1$. In the distractor-present condition we analysed the effects of target colour repetition and singleton distractor colour repetition. Repetition of target colour speeded RT by about 40 ms, $F(1, 5) = 12.68$, $p =$
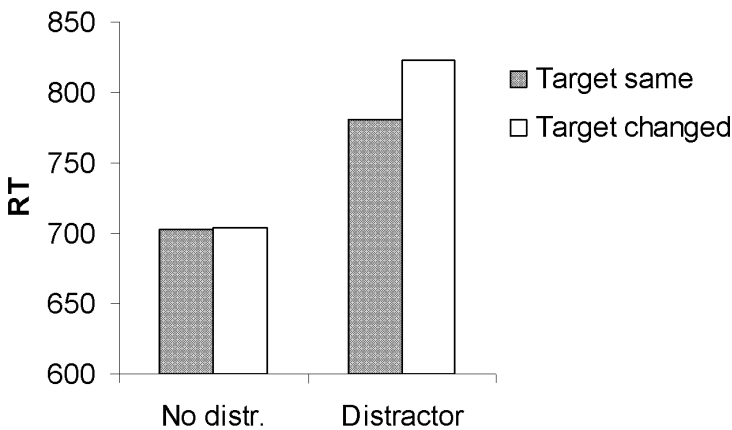
Figure 5.   Mean RT in Experiment 3 as a function of whether or not a singleton distractor was present in the display, whether the target colour was repeated or changed from the previous trial.

.016, $MSE = 851.1$, while repetition of distractor colour speeded RT by about 10 ms, $F(1, 5) = 24.72$, $p = .004$, $MSE = 22.4$. There was no interaction between the two factors ($F < 1$).

The results show that intertrial priming is modulated by the presence of a singleton distractor, as predicted by our hypothesis that the presence of a singleton distractor increases competition and thus ambiguity in the display. Note though that overall the intertrial priming effects were smaller than in Experiment 1. In the no singleton distractor condition they were even absent, although on the surface this condition seems similar to the 12 element conditions of Experiments 1 and 2, in which 30 and 25 ms priming effects were found. This difference is likely due to the fact that in Experiment 3 the colour of the nontarget elements was always grey (except for the singleton distractor), whereas in Experiment 1 the target and nontargets switched colour (i.e., on switch trials a red target among green nontargets was followed by a green target among red nontargets). Boosting the salience of the target colour increases nontarget salience if target and nontarget colours switch, leading to stronger competition. This may explain why priming was found in the 12 element condition of Experiment 1, and not in the no distractor condition of Experiment 3.

A similar factor may also explain the results of Hillstrom (2000). In her Experiment 3 a singleton distractor was added to the display. Contrary to our results, she failed to find any increase in priming effects as compared to a condition without such singleton distractor in her Experiment 1. However, just like in our experiments, the nontarget colour remained constant in the singleton condition, whereas targets and nontargets exchanged colour in the nonsingleton condition. Thus, in Hillstrom's experiments, the colour switch may have increased priming to a similar extent as adding a singleton distractor does. This factor may thus explain why Hillstrom did not find an effect of an added singleton distractor, while we did.

We also analysed the effect of response repetition—whether or not the response on two following trials was the same—on reaction time. For trials without a distractor, there was no effect of response repetition ($F < 1$), nor was there an interaction with target repetition ($F < 1$). For trials on which a distractor was present, no main effect of response repetition was found ($F < 1$). However, there was an interaction between target and response repetition: Target repetition had a larger effect when responses were repeated (59 ms) than when they were not (30 ms), $F(1, 5) = 11.44$, $p = .02$, $MSE = 456.8$. As predicted by the response selection view of priming, intertrial priming is thus especially strong when both the stimulus and the required response remain the same from one trial to the next. Contrary to the response selection view, however, repetition of the target stimulus was beneficial both when the response did and did not remain the same, as evidenced by a main effect of target repetition, $F(1, 5) = 14,26$, $p = .013$, $MSE = 464.0$.

GENERAL DISCUSSION

The experiments presented here show that intertrial priming in visual search is by no means an immutable phenomenon. Experiment 1 showed that intertrial priming is influenced by the number of elements that observers have to search: Large effects were found when the search display contained just three elements, increasing competition for selection. Much smaller intertrial priming effects were found with twelve element displays, when target identity was less ambiguous. The main finding of Experiment 3 was that the presence of a singleton distractor modulated the intertrial priming. In the no singleton distractor condition of Experiment 3 no intertrial priming was found, whereas a substantial priming effect was present when a singleton distractor was included in the displays.

Findings from both experiments are in line with the ambiguity resolution hypothesis set out at the beginning of this paper; an increase in the ambiguity of target identity increased intertrial priming effects in both experiments. They are not consistent with pure response selection views of intertrial priming. Our findings show that changes in the stimulus can substantially affect intertrial priming even when the response requirements remain the same. This goes against views in which intertrial priming only results from faster selection of the correct response when the target is repeated.

Our findings are also not consistent with pure visual selection views of intertrial priming. These views state that selecting a target results in its defining features (or dimensions) being more activated, efficiently allowing for repeated selection. However, since these accounts focus on the activation of target properties, they do not straightforwardly predict the influence of other display properties such as the set size or the presence of a singleton distractor. Moreover, from the literature, it is clear that response factors also mediate intertrial priming (Huang et al., 2004; Kumada, 2001; Olivers & Meeter, in press). This is confirmed by our finding in Experiment 3 that benefits of a repeated target were larger when the required response was also repeated.

It thus seems that intertrial priming can occur at any processing step, from attentional selection to response execution. It does not invariably occur, as failings to observe intertrial priming reported in the literature (Kumada, 2001) and in our Experiment 3 have shown. We have proposed ambiguity as a factor determining whether or not intertrial priming occurs in visual search. If it is ambiguous what the required response is, response selection will rely more heavily on what response was coupled with a stimulus on previous trials. If it is ambiguous what the target is, visual selection is helped by the increasing salience of target features of the previous trials, as found in electrophysiological recordings (Bichot & Schall, 2002). In the experiments reported here, ambiguity took the form of increased competition for visual selection.

Although in the discussion above we suggested that target features may gain a competitive advantage, it might be more correct to say that the target as a

whole becomes more salient. Findings from Huang et al. (2004) suggest that in the representations underlying priming, all features of the target are bound together. They varied target identity on three dimensions: Colour, size, and orientation (with the latter being the response feature). Intertrial priming was large when all target dimensions were repeated, but when one feature changed, repetition of the other features could even have a detrimental effect. This suggests that the representations involved are at the level of so-called object files, storing integrated objects (Treisman, 1992). Also consistent with this is the fact that intertrial priming driven by target identity is not dependent on the target appearing twice at the same location (Maljkovic & Nakayama, 1994).[2]

Goolsby and Suzuki (2001) showed that it is not necessary for the participant to search for the target during the previous trial for intertrial priming to occur. They used the paradigm of Maljkovic and Nakayama (1994) with three diamonds, of which one was the target by virtue of its unique colour. On some trials, they cued the target position. Such trials, on which no search was necessary, still evoked intertrial priming: After a trial in which a spatial cue revealed target position, reactions were still speeded on a subsequent search trial if the target had the same colour (as mentioned earlier, there was no intertrial priming on the trials in which the target was cued). However, intertrial priming only occurred when the target element was attended: When a distractor element was cued (i.e., an element that was not a colour singleton), no intertrial priming was found. This suggests that the target must be attended, and the task must remain constant.

Alternative episodic theories

The results reported here are inconsistent with a view in which priming results solely from episodic retrieval of responses. They are more consistent with two other episodic views on priming. In both, retrieval of episodic memories from previous trials is thought to aid processing, but at different stages than response selection. Hillstrom (2000) suggested that retrieval of previous trials has an influence on the prioritization rules underlying visual selection. By retrieving previous targets, participants would reestablish the prioritization settings that led to the finding of these targets. However, note that this idea is very difficult to distinguish from a visual selection view, in which the prioritization settings are more directly altered by the preceding trial. Moreover Hillstrom's proposal does not explicitly include a role for ambiguity.

Another episodic retrieval account has focused on a different processing step. According to Huang et al. (2004), participants will, after selecting the target,

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[2] Our point is not that a repetition of target location or of the visual configuration cannot deliver benefits, as it has been demonstrated that they can (Chun & Jiang, 1998; Chun & Nakayama, 2000; Maljkovic & Nakayama, 1996), but only that the benefits of target repetition are independent of those that accrue from position repetition (Maljkovic & Nakayama, 1996).

experience insecurity about whether they have selected the right element. They will therefore engage in a ''checking'' process to ascertain that the element they have selected is indeed the target. Retrieval of previous trials will help in this process, as a memory of the previous target will help the participant ascertain that the currently selected element is indeed a target. This is a plausible account of priming in their task, in which targets could be either smaller or larger than nontarget elements, but always matched memories from previous targets. In the basic Maljkovic and Nakayama (1994) paradigm (the three element condition in our Experiment 1), however, it is difficult to see how a checking procedure focused on the target could help participants. Only its status as a colour singleton defines the target as a target; only a procedure centred on the whole display can thus ascertain that the target is indeed the target. This is not what Huang et al. propose, however: The checking procedure is based on a comparison of the target alone with target memories (a ''rechecking'' of the whole display would come down to selecting the target for a second time, and would not benefit from memories of previous trials).

Alternative search-oriented theories

The addition of a singleton distractor, as in Experiment 3, has been hypothesized to change the nature of the search process. When the target is not unique in its uniqueness, observers may switch from singleton detection mode to feature detection mode (Bacon & Egeth, 1994), or from diffuse attention to more focused attention (Bravo & Nakayama, 1992). Bacon and Egeth surmise that observers in singleton detection mode will select any singleton in the display. When this strategy does not yield the target in a sufficient number of trials, observers will explicitly search for the feature defining the target, and thus disregard singletons that do not match the singleton definition. Bravo and Nakayama state that observers will look for feature discontinuities when there is only one singleton, widely distributing attention across the display. Although Bravo and Nakayama do not discuss the case that there is more than one feature singleton, they suggest that observers can restrict their attention to part of the display in order to exclude interfering information. In this case, feature discontinuities are less easy to observe, and therefore the specific feature values of the target will play a greater role in visual search (Bravo & Nakayama, 1992).

One could imagine that these changes in the character of the search underlie the presence or absence of intertrial priming. Intertrial priming in visual search may only occur, for example, when the task induces participants to divide their attention over the whole display and not focus closely on the target. This hypothesis, that unfocused attention is required for intertrial priming to occur, was in fact proposed by Kumada (2001). However, he rejected it because he did not find intertrial priming in a texture comparison task that did not require focused attention. Moreover, such a hypothesis would also be at odds with our

result in Experiment 3 that intertrial priming is present for displays with a salient singleton distractor, but absent for displays without one.

Alternatively, intertrial priming may depend on the search mode used: It may be present for feature search mode, and absent for singleton detection mode. Although such a hypothesis would explain the results of Experiment 3, it would not elucidate findings from Experiment 1. It is not, a priori, clear why participants would use feature search in that experiment, as no feature predicted what the target would be. It thus seems to be impossible to identify a type of visual search that accommodates intertrial priming, to the exclusion of other types of search.

Conclusion

We have shown that manipulations affecting search can influence the presence and size of intertrial priming effects. We have also presented a new hypothesis that attempts to explain when priming occurs and when it does not. Whether or not our hypothesis covers all the facts, we hope to have established that a theory of intertrial priming must not only explain that it occurs, but also why it sometimes does and sometimes does not occur.

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