Cross-dimensional interference and cross-trial inhibition

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In two experiments, we examined whether one source of cross-dimensional interference in visual search involves cross-trial position priming. In Experiment 1, we demonstrated cross-dimensional interference in search for an orientation-defined target: Search for a left-tilted target among right-tilted non-targets was disrupted by the presence of a singleton color distractor. In all conditions, search was facilitated when a target was presented at the same position as a target in the previous trial (positive position priming). In addition, there were negative effects of position priming on orientation targets that fell on the same side as singleton distractors on the previous trial. In Experiment 2, to examine the impact of negative position priming on cross-dimensional interference, trials with and without singleton distractors were presented in a single trial block. The chance of a singleton distractor's being present on a preceding trial was then equated across displays when the distractor was and when it was not subsequently present. Cross-dimensional interference was eliminated under this mixed presentation condition, suggesting that the cost of cross-dimensional interference was not determined by the stimulus-driven factors in the current trial, at least when a limited number of target and distractor locations was used. We conclude that top-down selection is possible during visual search, and this leads to inhibition of the location of salient distractors. The cost of this is slowed detection of targets at inhibited locations on subsequent trials.

In order to understand visual attention, it is important to know whether we are able to limit selection to a goal-defined feature of the environment or whether selection is determined in a more bottom-up manner. Theeuwes (1991) examined the effectiveness of top-down selection by presenting two feature singletons in a visual search task. For example, in his Experiment 2, colored elements were arranged around a fixation point. Targets were defined by a unique attribute: a color or a shape. These singleton targets could also appear with singleton distractors, where the unique attribute was not defined as a target feature for the task. On trials in which the target was defined by its color, a distractor might have a unique shape. On trials in which the target was defined by its shape, the distractor might have a unique color. Subjects had to discriminate orientation of a line segment presented in a target. For targets defined by color, there was no difference in reaction times (RTs) when (shape) singleton distractors were or were not present. However, for targets defined by shape, RTs were slowed when the (color) singleton distractor was present, relative to when it was absent: There was cross-dimensional interference. Asymmetric cross-dimensional interference has subsequently been reported with other dimensions, including color and luminance (Theeuwes, 1991), color and

onset (Theeuwes, 1994), and color and orientation (Kumada, 1999). Cross-dimensional interference suggests that selection cannot be constrained solely by top-down factors, since stimuli from a dimension not defined for selection disrupt performance.

The most important factor affecting asymmetric cross-dimensional interference is the relative saliency of the target and the singleton distractor. Theeuwes (1991) showed that when the discriminability of color singletons decreased, shape singleton distractors interfered with search for a color target, whereas a color singleton distractor did not interfere with search for a shape target. To explain these results, Theeuwes (1991) argued that attention is captured by the most salient features in a display, irrespective of their relation to the goal of the task. When the most salient feature is the target, RTs are unaffected by the presence of an irrelevant singleton distractor. On the other hand, when the target is less salient than a singleton distractor, attention is unintentionally drawn to the distractor, slowing RTs. Theeuwes (1991) concluded that asymmetrical cross-dimensional interference provided evidence for a failure of top-down control over visual selection.

Contrasting data have been provided by Folk and colleagues, using a form of spatial precuing (Folk & Remington, 1998; Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994). In Folk and Remington, a target display consisted of four characters in four boxes around a fixation point. Subjects had to determine whether a character indicated by a target color was an "X" or an "=". Before target displays were presented, however, a distractor display occurred, consisting of four sets of four small cir-

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cles. Each set of circles was presented around each box. In the same-color condition, one of four sets of circles had the same color as a target, and the other three sets of circles were white. In the different-color condition, just one set of circles had a different color from the target, and this was also unique relative to the other sets of circles. The stimulus onset asynchrony (SOA) between the distractor display and the target display was 150 msec. In the same-color condition, RTs to discriminate a target were faster when the same-color distractor was presented at the same location as the target, relative to when it appeared at a different location. They suggested that this result was caused by an involuntary shift of attention to the location of the (color) feature defining the target. In the different-color condition, however, there was no effect of the location of the unique distractor on RTs. That is, there was no involuntary capturing of attention. From this, they concluded that top-down selectivity based on feature values is possible, even when the target itself is a singleton.

One finding reported by Folk and Remington (1998) may help to explain the apparent inconsistency between the results. In their Experiment 2, a condition with no singleton distractors was used, in which all the sets of circles in a distractor display were white. RTs in this condition were compared with those in the different-color condition. Although RTs in the different-color condition were unaffected by the location of the singleton distractor relative to the target, they were significantly longer than those in the no-distractor condition. They argued that this type of cost in RT was dissociable from effects that were due to capture of spatial attention and might reflect a form of nonspatial *filtering cost* (Kahneman, Treisman, & Burkell, 1983). It is possible that filtering costs of some form contribute to singleton interference effects (cf. Theeuwes, 1991), a point we will return to in the General Discussion section.

From the prior results in the literature, the degree to which we can control visual selection remains unclear. The data from Folk and colleagues suggest that color singletons (as distractors) do not necessarily capture attention when the target is defined by a different color. However, in cases in which the target's dimension is undefined (or perhaps, when participants are in a "singleton detection mode" form of search; see Bacon & Egeth, 1994), singleton distractors can affect target detection (Theeuwes, 1991).

In this study we examined cross-dimensional interference from singleton distractors by studying performance not only on the trial in which singleton distractors occur, but also on subsequent trials. Several recent experiments on visual search have shown that RTs are affected not only by the properties of the current display, but also by those of prior displays. For example, RTs are faster if consecutive targets belong to the same feature dimension than if they belong to different feature dimensions (Found & Müller, 1996; Treisman, 1988), and detection is improved when successive targets fall at the same location (Maljkovic & Nakayama, 1996). Thus, target detection can be

primed by recent events. Priming can be negative as well as positive. Cepeda, Cave, Bichot, and Kim (1998), for example, have shown inhibition of detection when probes are presented at the location of distractors following search for a color-defined target. Similar effects have been reported by Klein (1988) when probes fall at the locations of distractors in conjunction search and by Watson and Humphreys (in press) when probes fall at the locations of distractors that precede target displays. Of particular relevance to the present study, Kim and Cave (1999) also found probe inhibition at the location where singleton distractors appeared, using displays like Theeuwes (1992). This last result suggests that the positions of salient distractors may be actually inhibited and also that this can affect the processing of stimuli presented subsequently at the same location. Such inhibition can be conceptualized in several ways. For instance, it may reflect a form of inhibition of return (Maylor, 1985; Posner & Cohen, 1984), following the capture of attention by the singleton target. Alternatively, it may reflect the effect of parallel computation between targets and distractors, with strong competitors for target selection being subject to maximal inhibition (Houghton, Tipper, Weaver, & Shore, 1996; Tipper, Howard, & Houghton, 2000). We return to accounts of the inhibition effect in Experiment 2. Whichever account is upheld, however, these results open up the possibility that at least part of the cross-dimensional interference effect found in search is due to inhibition of targets that fall at the locations of singleton distractors in previous displays; we term this *across-trial inhibition*. We evaluated whether across-trial inhibition can contribute to cross-dimensional interference. In Experiment 1, we examined performance contingent not only on the displays present on a given trial, but also on those presented on preceding trials. In Experiment 2, we presented singleton trials mixed with trials on which no singleton distractor was presented. This meant that trials in which such distractors were present and trials in which they were absent were equally likely to both precede and follow one another. Across-trial inhibition should then be equated on trials in which singleton distractors are present and those in which they are absent. Under this circumstance, we can obtain a "pure" measure of within-trial cross-dimensional interference.

EXPERIMENT 1

Experiment 1 was designed to investigate whether cross-dimensional interference was affected by effects occurring across trials. Subjects searched for a target defined by color or by orientation in an array of nontargets. In the color target condition, either the orientations of the distractors were homogenous or one distractor differed in orientation relative to the others (the singleton distractor). In the orientation target condition, either the colors of the distractors were homogenous or one was different. The target was always presented at one of four positions, and the singleton distractor, when presented, appeared at one of two

positions on the opposite side of the visual field to the target. Trials in which singleton distractors were presented were given in a separate block from those in which singleton distractors were absent. RTs to the target were analyzed on the basis of the relation between the position of a target on a current trial (n) and either that of a target on the previous trial ($n - 1$) or that of a singleton distractor on the previous trial ($n - 1$).

Method

Subjects. Eight undergraduate students (3 males and 5 females; 19–20 years of age) participated for partial fulfillment of course credit. All had normal or corrected-to-normal visual acuity and normal color vision.

Apparatus and Stimuli. Visual stimuli were generated by a microcomputer (Apple Macintosh) and were presented on a 13-in. color CRT display (Apple Color Monitor). The display elements, which were the same as those in Experiment 6 of Kumada (1999), were composed of a green open rectangle (15×6 mm; $1.5^\circ \times 0.6^\circ$) and a line that horizontally intersected the rectangle by one-third or two-thirds position from the top of the rectangle (see Figure 1). There were three levels of display size, defined by the total number of display elements: 6, 9, and 12. The elements were randomly scattered in cells of an imaginary 4×5 matrix (80×100 mm; $8^\circ \times 10^\circ$ of visual angle).

There were two target conditions: a color target condition and an orientation target condition. Under both target conditions, the non-targets were green rectangles tilted 45° to the right from their vertical orientation. The color target was a red rectangle tilted 45° to the right. The orientation target was a green rectangle tilted 45° to the left. For each target condition, displays either contained or did not contain

a singleton distractor (no-distractor and distractor conditions). With color targets, the singleton distractor was a green rectangle tilted 45° to left of vertical orientation. With orientation targets, the singleton distractor was a red rectangle tilted 45° to the right of vertical.

For both distractor and no-distractor displays, the target could occur in one of four positions in the display, two on the left side of the display and two on the right side (see Figure 1). On distractor trials, the singleton distractor was presented in one of the two target positions on the opposite side of fixation relative to the target.

Procedure. The subjects were seated 50 cm from the CRT display. The sequence of each trial was as follows. First, a small white dot was presented as a fixation point in the center of the display for 1 sec. After 200 msec of blank field, a visual search display was presented until the subject responded. After 1 sec of a blank interval, the fixation point for the next trial was presented. The response-stimulus interval was 2,200 msec. The subject's task was to search for a prespecified target and to respond to the relative location of the line segment (upper or lower) within the target as quickly and accurately as possible by pressing one of two keys. The two keys were assigned to the index fingers of each hand; the left index finger to indicate *upper*, and the right to indicate *lower*. The subjects were instructed to fixate the fixation point when it was presented on the display.

All conditions were performed in a within-subjects design. For each target condition (color or orientation), distractor and no-distractor trials were each presented in two separate blocks. Each block was composed of 96 trials (3 display sizes $\times$ 2 responses $\times$ 16 repetitions) in random order. All the subjects received eight blocks of trials (two target conditions $\times$ two distractor conditions $\times$ two replications); 4 subjects started off with four blocks of the color target condition, and the other 4 subjects started off with four blocks of the orientation target condition. The order of presentation of the blocks of distractor and no-distractor trials was counterbalanced across the subjects.

Figure 1. Example display used Experiment 1. Solid rectangles were green and dotted rectangles were red. Target position in each display represents four possible target positions.

Before the first block of each condition, the subjects received 40 trials of practice.

Results

Cross-dimensional interference. The RT outliers were discarded using a modified recursive outlier elimination procedure (Van Selst & Jolicoeur, 1994). This resulted in the removal of 2.80% of all observations.

The mean correct RTs are plotted as a function of the display size in Figure 2. A three-way analysis of variance (ANOVA) was performed, with main terms being the target condition, the distractor condition, and the display size. All the main effects were significant [target condition, $F(1,7) = 15.96, p < .01$; distractor condition, $F(1,7) = 7.47, p < .05$; display size, $F(2,14) = 21.35, p < .0001$]. Two two-way interactions were significant [target $\times$ distractor, $F(1,7) = 6.59, p < .05$; target $\times$ display size, $F(2,14) = 7.94, p < .01$]. No other interactions were significant. The effect of the display size was the same on distractor and no-distractor trials. The effect of the distractor was further examined with two-way ANOVAs, with effects of the distractor and the display size. In the color target condition, the main effect of display size was significant [$F(2,14) = 5.66, p < .05$], but the main effect of the distractor and the two-way interaction were not reliable. In the orientation target condition, both main effects were significant [distractor, $F(1,7) = 7.13, p < .05$; display size, $F(2,14) = 19.70, p < .0001$]. The two-way interaction was not significant. The effect of the distractor was significant only in the orientation target condition. These results were consistent with previous studies showing asymmetrical cross-dimensional interference between color and orientation (Kumada, 1999).

The slope of the RT function was determined by linear regression analyses of the mean RTs. For distractor and

Table 1
Error Rates (in Percentages) for Each Condition
in Experiment 1

Condition	Display Size		
	6	9	12
Color Target Conditions			
No distractor	2.15	2.15	2.73
Distractor	2.93	1.95	1.76
Orientation Target Conditions			
No distractor	2.73	2.54	3.13
Distractor	1.76	3.91	2.54

no-distractor trials, the slopes for the color target condition were 3.56 and 2.08 msec/element, and those for the orientation target condition were 7.05 and 9.78 msec/element, respectively.

Table 1 shows error rates in each condition. Error rates were subjected to an arcsine transformation and entered into a three-way (target $\times$ distractor $\times$ display size) ANOVA. None of the main effects or interactions was significant ($p > .05$). The error rates remained constant under all conditions, suggesting that the subjects did not exhibit a speed-accuracy tradeoff.

Intertrial RT analysis. The intertrial effects of both targets and singleton distractors were examined. RTs on each trial (i.e., n trial) were analyzed with respect to the location of a target and the singleton distractor on the previous ($n - 1$) trial. For this analysis, the three levels of display size were pooled. On a no-distractor trial, RTs on trial n fell into three categories with respect to the location of a target on trial $n - 1$. If a target on trial n was presented in the same position as that on trial $n - 1$, RTs on trial n were categorized as *same-position target*. If a target on trial n was presented on the same side of the visual field, but in a different position relative to the target on trial $n - 1$, RTs on trial n were categorized as *same-side target*. If the target on trial n was presented on the opposite side of the visual field relative to the target on trial $n - 1$, RTs on trial n were categorized as *opposite-side target*. On distractor trials, RTs on each trial were categorized with respect to the location of a target on trial n relative to the location of a target and a singleton distractor on trial $n - 1$. The location of a singleton distractor on the current trial and its location on trial n relative to its position on trial $n - 1$ were not taken into account. The categories of *same-position target* and *same-side target* were the same as on no-distractor trials. However, since a singleton distractor was always presented on the opposite side relative to the target, RTs in the opposite-side condition could be classified with respect to the location of the singleton distractor on trial $n - 1$. If a target on trial n was presented in the same position as a singleton distractor on trial $n - 1$, RTs on trial n were categorized as *opposite: same-position distractor*. If a target on trial n was presented in a different position from that of the singleton distractor on trial $n - 1$, but on the same side of fixation, RTs on trial n were categorized as *opposite: same-side distractor*. Figure 3 shows the mean RTs as

Figure 2. Mean correct reaction times as a function of condition and display size.

a function of the intertrial relation between the current target position and the status of trial $n - 1$.

For each target and distractor condition, the effect of the position of a target was examined with separate one-way ANOVAs, with a main effect of target position. On no-distractor trials with color targets, the main effect of target position was significant [$F(2,14) = 11.65, p < .001$]. Planned F contrast analyses revealed significant differences between same-position target and same-side target trials [$F(1,14) = 10.44, p < .01$] and between same-position target and opposite-side targets [$F(1,14) = 22.30, p < .0005$] and no significant difference between same-side and opposite-side targets ($p = .158$).

On distractor trials with the same target, there was again a reliable effect of target position [$F(2,14) = 5.52, p < .01$]. RTs were fastest to targets presented at the same position on trials $n - 1$ and n . Planned F contrasts revealed a marginally significant difference between same-position and same-side target trials [$F(1,14) = 4.20, p = .053$] and a significant difference between same-position targets and the two opposite-position conditions [with same-side and same-position distractors, $F(1,14) = 9.75, p < .01$, and $F(1,14) = 14.48, p < .001$, respectively]. Other contrasts were not significant.

On no-distractor trials with orientation targets, the main effect of target position was significant [$F(2,14) = 17.33, p < .0005$]. There were significant differences between the same-position and the same-side target trials [$F(1,14) = 20.11, p < .0005$] and between the same-position and the opposite-side targets [$F(1,14) = 30.76, p < .0001$]; there was no significant difference between same-side and opposite-side targets ($p = .306$). This pattern of results was identical to that on no-distractor trials for the color target condition.

Figure 3. Mean correct reaction times as a function of condition and the status of the target position in trial $n - 1$. SPT, same-position target; SST, same-side target; OST, opposite-side target; O:SSD, opposite: same-side distractor; O:SPD, opposite: same-position distractor.

On distractor trials with orientation targets, there was again a main effect of the target position [$F(2,14) = 13.11, p < .0001$], which can be decomposed as follows. There was a significant advantage for same-position targets over other targets [vs. same-side targets, $F(1,14) = 9.33, p < .001$; vs. opposite: same-side distractors, $F(1,14) = 28.24, p < .0001$; vs. opposite: same-position distractors, $F(1,14) = 30.06, p < .0001$]. RTs in the same-side target condition were also significantly faster than those in the two opposite-side conditions [with same-side and same-position distractors, $F(1,14) = 5.10, p < .05$, and $F(1,14) = 5.90, p < .05$, respectively]. However, there was no sign of a difference between the two opposite-side conditions (with same-side and same-position distractors, $p = .868$).

Discussion

First, our results replicated asymmetrical cross-dimensional interference in visual search tasks (Bacon & Egeth, 1994; Kumada, 1999; Theeuwes, 1991, 1992, 1994). A singleton distractor significantly delayed RTs to a target only in the orientation target condition. This may be attributed to the greater salience of color over orientation singletons here, as is evidenced by performance on the no-distractor baseline trials.

The results of the intertrial RT analysis were also quite clear. For both color and orientation targets, RTs were faster to targets that appeared in the same position as the target on the previous trial than to targets presented in the other positions on trial $n - 1$. This positive effect of position priming has been reported previously in efficient, single-feature search tasks (Maljkovic & Nakayama, 1996). Our results indicate that this positive priming effect was spatially limited, being greater for targets falling in the same location than for targets falling on the same side of fixation. For color targets, the effect was 16.5 and 12.6 msec on no-distractor and distractor trials. For orientation targets, the effect was 37.2 and 38.2 msec on no-distractor and distractor trials, as compared with the same-side condition. The size of the positive priming effect did not interact with the presence of a singleton distractor, but it did depend on the feature dimension of the target (being larger for orientation targets).

In the orientation target condition, RTs for same-side targets were faster than those for opposite-side targets, but only when singleton distractors were present. Thus, the effect was primarily due to these distractors. It appears that RTs to targets were slowed when they were presented at locations formerly occupied by distractors. The size of this negative position priming effect was 28.3 msec when distractors previously fell on the same side as targets and 30.4 msec when distractors previously fell at the same position. There was no difference between these latter conditions [$t(7) = 0.196, p = .850$, two-tailed]. Thus, in contrast to positive position priming, negative position priming (at the location of a salient distractor) seems either to involve a broader spatial spread or even to involve a whole hemifield. We return to this point in the General Discussion section. Our finding of negative position priming at the loca-

tion of former singleton distractors is consistent with evidence of inhibition at distractor locations in search tasks (Kim & Cave, 1999; Klein, 1988; Watson & Humphreys, 2000). It appears that inhibition is applied to help reject distractors and that this can carry over across time to influence performance on subsequent trials. This occurred here even though the search tasks were relatively easy and seemed to be based on spatially parallel detection processes (judging from the slopes of the search functions).

EXPERIMENT 2

Our demonstration of negative position priming across trials from rejected singleton distractors also raises the possibility that this form of carryover effect could contribute to cross-dimensional interference effects in search. Previous studies of cross-dimensional interference have assumed that it stems from the presence of a salient singleton distractor on a trial; that is, it is a *within-trial effect* (Kumada, 1999; Theeuwes, 1991, 1992, 1994). However, when singleton distractor trials are presented in a single block, negative position priming across trials will slow RTs. There will be no similar negative carryover on no-distractor trials, with the result being that no-distractor trials will be faster. The result is that RTs are slower on distractor than on no-distractor trials, owing not to within-trial attentional capture, but to across-trial priming.

To examine this last possibility, we presented mixed no-distractor and distractor trials in Experiment 2, in addition to single-distractor and no-distractor blocks (as in Experiment 1). With mixed presentations, both distractor and no-distractor trials are equally likely to be preceded by a trial in which the singleton distractor is present (or absent). When trial $n - 1$ contains a singleton distractor, negative position priming will affect performance on trial n for both distractor and no-distractor trials. When trial $n - 1$ is a no-distractor trial, there will be no negative position priming, but this will again hold for both distractor and no-distractor trials. If negative across-trial effects contribute to cross-dimensional interference, the interference effects in the mixed condition should be less than those in the blocked conditions. If there is no within-trial interference over and above the cross-trial effects, cross-dimensional interference may even be eliminated in the mixed condition.

As far as we know, most previous studies reporting cross-dimensional interference have presented distractor and no-distractor trials in separate blocks (Bacon & Egeth, 1994; Kumada, 1999; Theeuwes, 1991, 1992, 1994). Mixed presentation conditions have been used in three studies (one cited in the discussion of Experiment 1 of Bacon and Egeth, 1994; Theeuwes, 1995; also, Experiment 3 in Folk & Remington, 1998). Although significant effects of singleton distractors have been reported, the interference effects appear to be reduced (compare Figures 4 and 5 in Folk & Remington, 1998). However, these studies did not include a direct comparison between the blocked and the mixture presentation conditions using

a within-subjects design, so the effect of the mixture presentation remains untested.

Method

Subjects. Eight new undergraduate students (3 males and 5 females; 19–20 years of age) participated for course credit. All had normal or corrected-to-normal visual acuity and normal color vision.

Apparatus and Stimuli. The apparatus and stimuli were the same as those used in Experiment 1, except that only orientation targets were used. There were four condition blocks: no-distractor, distractor, and two mixture blocks. The no-distractor and distractor blocks were the same as those in Experiment 1. In the two mixture blocks, no-distractor and distractor trials were presented in one block. In the low-distractor condition, one trial block consisted of 60 no-distractor trials and 36 distractor trials. In the high-distractor condition, one trial block consisted of 36 no-distractor trials and 60 distractor trials. In all the trial blocks, there were equal numbers of trials for each of three levels of display size.

Procedure. The procedure was the same as that in Experiment 1. All conditions were performed within-subjects. All the subjects received 2 no-distractor blocks, 4 low-distractor blocks, 4 high-distractor blocks, and 2 full-distractor blocks. The order of presentation of these 12 blocks was counterbalanced across the subjects. Before the presentation of the first block, the subjects received 40 trials of practice with 20 no-distractor and 20 distractor trials presented in random order.

Results

Cross-dimensional interference. RT outliers were excluded from the analysis by the same procedure as that used in Experiment 1. This resulted in the removal of 2.41% of all the observations.

Figure 4 shows the mean RTs as a function of the display size. In the “pure” blocks (Figure 4A), RTs were slower on distractor than on no-distractor trials. This was confirmed in a two-way ANOVA, with the main terms of distractor (no-distractor/distractor) and display size. The main effects of the distractor and the display size were significant [distractor, $F(1,7) = 19.21, p < .005$; display size, $F(2,14) = 27.02, p < .0001$]. The distractor $\times$ display size interaction was not significant ($p = .171$). RTs on no-distractor trials were 41.5 msec faster than those on distractor trials. Slope of the RT function for no-distractor trials was 4.02 msec/element, whereas it was 7.26 msec/element on distractor trials.

In the low- and high-distractor conditions (Figures 4B and 4C), separate two-way ANOVAs with the main terms of distractor and display size were performed. In the low-distractor condition, the effect of the display size was significant [$F(2,14) = 17.69, p < .0001$]. Neither the main effect of the distractor nor the distractor $\times$ display size interaction was significant ($ps > .30$). The slope for no-distractor trials was 3.67 msec/element, whereas for distractor trials it was 6.45 msec/element. Similar results occurred in the high-distractor condition. The effect of display size was significant [$F(2,14) = 10.27, p < .005$], but the main effect of the distractor and the distractor $\times$ display size interaction were not ($ps > .20$). The slope for no-distractor trials was 9.05 msec/element, and for distractor trials it was 6.56 msec/element.

Figure 4. Mean correct reaction time as a function of condition and display size for “pure” blocks (A), low-distractor blocks (B), and high-distractor blocks (C).

To compare performance across the no-distractor conditions, a further ANOVA was conducted that included data from the pure and mixed blocks (separated for high and low distractors). The main effects of block and display size were significant [$F(2,14) = 4.03, p < .05$, and $F(2,14) = 12.29, p < .0001$, respectively]. The block $\times$ display size interaction was also significant [$F(4,28) = 3.06, p < .05$]. RTs in the high-distractor block were significantly longer than those in the pure no-distractor block [$F(1,14) = 7.99, p < .05$]. There was no difference in RTs between the pure block and the low-distractor block ($p = .254$). The results show that high proportions of singleton distractors, in the mixed blocks, slowed RTs on no-distractor trials. A similar analysis was undertaken on distractor trials. The main effect of display size was again significant [$F(2,14) = 24.49, p < .0001$], whereas the effects of block and the block $\times$ display size interaction were not significant ($ps > .10$). Planned F contrasts revealed a single difference across the blocks, with the pure distractor block being slower than the low-distractor block [low distractor vs. distractor, $F(1,14) = 4.71, p < .05$]. The trend for RTs in the pure blocks to be slower than those in the high-distractor block was not reliable.

Error rates were arcsine transformed and entered into a three-way ANOVA, with main terms of block, distractor, and display size. Only a block $\times$ display size interaction was significant [$F(4,28) = 3.12, p < .05$]. This was due

to the fact that error rates of six-element trials in the low-distractor blocks (0.91%) were lower than those of six-element trials in other blocks (2.66%–3.13%) and also of other display sizes in the low-distractor block (2.26%–4.38%). These trends were not compatible with those of RTs, suggesting no speed–accuracy tradeoff.

Intertrial RT analysis. RTs on trial n were examined with respect to the intertrial relation of targets and distractors (if presented). First, each display was categorized with respect to the presence of distractors in the current trial and in the preceding trial. In mixed blocks, there were four types of intertrial transition: no distractor in the preceding trial ($n - 1$) and no distractor in the current trial (N–N transition), no distractor in trial $n - 1$ and distractor in trial n (N–D transition), distractor in trial $n - 1$ and no distractor in trial n (D–N transition), and distractor in trial $n - 1$ and distractor in trial n (D–D transition). In the pure no-distractor blocks, only the N–N transitions were presented. Also, in the full-distractor block, only the D–D transitions were presented. Table 2 shows the RTs calculated with respect to the status of the target on trial $n - 1$ in the N–N transition. RTs were subjected to a two-way ANOVA, with main terms of block (no, low, and high) and $n - 1$ status (same-position target, same-side target, opposite-side target). The main effect of the $n - 1$ status was significant [$F(2,14) = 12.60, p < .001$]. The main effect of the block was not significant, but marginal

Table 2
Mean Reaction Time (RT, in Milliseconds) and Error Rate to a Target
on a No-Distractor Trial as a Function of the Relation to Target
on Trial $n - 1$ in Experiment 2 (N–N Transition)

Trial $n - 1$	Block Condition								
	No Distractor			Low Distractor			High Distractor		
	RT	<i>N</i>	% Error	RT	<i>N</i>	% Error	RT	<i>N</i>	% Error
Same-position target	527	45	2.12	542	33	1.66	548	13	1.25
Same-side target	549	42	2.48	558	39	2.44	596	12	1.25
Opposite-side target	562	86	2.84	580	65	3.82	597	22	3.72
Average	550			560			583		

Note—*N*, number of trials.

Table 3
Mean Reaction Time (RT, in Milliseconds) and Error Rate
to a Target on a No-Distractor Trial as a Function
of the Relation to Target and Singleton Distractor
on Trial $n - 1$ in Experiment 2 (D-N Transition)

Trial $n - 1$	Block Condition					
	Low Distractor			High Distractor		
	RT	<i>N</i>	% Error	RT	<i>N</i>	% Error
Same-position target	526	20	2.00	553	19	1.74
Same-side target	554	22	0.63	588	23	1.65
Opposite: same-side distractor	579	18	1.32	587	20	3.50
Opposite: same-position distractor	589	21	5.03	600	21	4.10
Average	562			583		

Note—*N*, number of trials.

[$F(2,14) = 2.77, p = .097$]. The interaction was not significant ($p > .50$). RTs for the same-position targets were faster than those in the other conditions ($ps < .005$). But there was no difference in RTs between the same-side target trials and the opposite-side target trials ($p = .166$).

Table 3 shows the RTs in the D-N transition. RTs were subjected to a two-way ANOVA, with main terms of block (low and high) and $n - 1$ status (same-position target, same-side target, opposite: same-side distractor, opposite: same-position distractor). The main effect of $n - 1$ status was significant [$F(3,21) = 11.53, p < .0001$], but the main effect of the block and the interaction were not ($ps > .10$). RTs were fastest on trials in which the targets fell at the same position on trials $n - 1$ and n , as compared with all the other conditions ($p < .05$ for all comparisons). RTs were also faster when targets fell on the same side across trials, as compared with when the target on trial n fell at the location of the singleton distractors on trial $n - 1$. The results indicate a positive effect of position priming between targets at the same location and a negative effect when the target appeared at the location of the prior singleton distractor (relative to when targets fell on the same side of fixation). These results held across both mixture sets.

Next, the N-D transition was analyzed, with performance separated according to where current targets and singleton distractors fell (on trial n) with respect to the position of the target on trial $n - 1$. Table 4 shows the breakdown of the data. RTs were subjected to a two-way ANOVA, with main terms of block (low and high) and the n to $n - 1$ relations. The main effect of the n to $n - 1$ status was sig-

nificant [$F(3,21) = 8.11, p < .001$]. The effect of block and the interaction were not significant ($ps > .10$). RTs were fastest when targets appeared at the same position ($p < .05$ for all comparisons, on planned F comparison tests). When targets fell on the same side across trials, RTs were faster than when the target on trial n fell at the location of the distractor on trial $n - 1$ ($p < .05$, planned F comparison test). There were no other reliable differences.

Finally, Table 5 shows RTs analyzed with respect to the status of the positions in $n - 1$ trials, where targets were presented, in the D-D transition. RTs were subjected to a two-way ANOVA, with main terms of block (low, high, and full) and the n to $n - 1$ relations. The main effect of the status was significant [$F(3,21) = 12.65, p < .0001$]. The main effect of the block was marginally significant [$F(2,14) = 3.05, p = .080$], but the interaction was not significant ($p = .78$). Again, RTs for targets in the same position were faster than those in the other conditions ($ps < .005$). Also, when targets fell on the same side across trials, RTs were faster than when the target on trial n fell at the location of the distractor on trial $n - 1$ ($p < .05$, planned F comparison test). There were no other reliable differences.

In all the intertrial analyses reported here, the results were quite similar. Only the main effect of status reached significance. The same-position target trials were faster than were the other trials, in which the target in the current trial fell in a position other than that for the target (positive position priming). In transitions from trials in which singleton distractors were presented, when targets fell on the same side across trials, RTs were faster than when the

Table 4
Mean Reaction Time (RT, in Milliseconds) and Error Rate to a Target
on a Distractor Trial as a Function of its Relation to Targets and Singleton Distractors
on Trial $n - 1$ in Experiment 2 (N-D Transition)

Status of Trial $n - 1$ in Target/Distractor Positions of Trial n		Block Condition					
		Low Distractor			High Distractor		
		RT	<i>N</i>	% Error	RT	<i>N</i>	% Error
Target	Distractor						
Same-position target	Opposite-side target	532	20	0.51	562	23	2.40
Same-side target	Opposite-side target	565	19	1.41	579	22	3.92
Opposite-side target	Same-position target	588	19	3.48	597	24	1.79
Opposite-side target	Same-side target	566	18	2.88	594	18	0.83
Average		562			583		

Note—*N*, number of trials.

Table 5
Mean Reaction Time (RT, in Milliseconds) and Error Rate to a Target on a Distractor Trial
as a Function of its Relation to Targets and Singleton Distractors on Trial $n - 1$
in Experiment 2 (D–D Transition)

Status of Trial $n - 1$ in Target/Distractor Positions of Trial n		Block Condition								
Target	Distractor	Low Distractor			High Distractor			Full Distractor		
		RT	<i>N</i>	% Error	RT	<i>N</i>	% Error	RT	<i>N</i>	% Error
Same-position target	Opposite-side target	532	11	2.50	557	30	3.76	560	41	4.27
Same-side target	Opposite-side target	566	15	1.56	581	32	5.18	581	45	3.55
Opposite-side target	Same-position target	584	14	0.96	599	34	3.42	611	40	5.16
Opposite-side target	Same-side target	564	12	1.25	593	32	3.50	607	40	5.13
Average		563			583			590		

Note—*N*, number of trials.

target on trial n fell at the location of the distractor on trial $n - 1$ (negative position priming). In addition, in the N–N transition and D–D transition, there were marginally significant effects of block. This was due to the trend that RTs in the low-distractor blocks were faster than those in the high-distractor blocks under these transitions.

Discussion

There were several important results. First, we replicated cross-dimensional interference effect when distractor and no-distractor trials occurred in separate pure-trial blocks. Distractor trials were then slower than no-distractor trials (Figure 4A). The size of this effect was almost identical to that found in Experiment 1 (42 msec here, 40 msec in Experiment 1). Second, cross-dimensional interference was eliminated in the mixed blocks, both when singleton targets appeared on low proportions of trials and when they appeared on high proportions of trials. If the source of the interference effect here was attentional capture within a trial (cf. Theeuwes, 1991, 1992, 1994), the effect should have occurred irrespective of whether distractor trials were mixed with no-distractor trials. Clearly, it did not. The intertrial analysis also showed that there was no effect of the singleton distractors in the current trials when the presence of singleton distractors in the preceding trials was equated: For instance, RTs in the N–N transition were the same as those in the N–D transition on average (560 vs. 562 msec in the low-distractor block; 583 vs. 583 msec in the high distractor block). Similar results were obtained in the D–N transition and in the D–D transition (562 vs. 563 msec in the low-distractor block; 583 vs. 583 msec in the high-distractor block).

Evidence of across-trial priming was again provided by the intertrial analysis. The D–N transition and the D–D transition showed similar results. Relative to when targets appeared on the same side of fixation across trials, RTs were speeded when targets fell at the same location, whereas RTs were retarded when targets fell at the location of singleton distractors on the preceding trials. There was positive priming when targets occupied the same position and negative priming when targets fell at the site formerly occupied by singleton distractors (again, relative to a baseline at which targets fell on the same side of fixation).

However, the intertrial analysis is not consistent with our preliminary hypothesis that the positional priming effect

might be directly associated with the cost of the cross-dimensional interference. This hypothesis predicted that RTs in the current trials should be affected by whether singleton distractors were presented in the directly preceding trials. The results were against this prediction: RTs in the N–N transition were the same as those in the D–N transition on average (560 vs. 562 msec in the low-distractor block; 583 vs. 583 msec in the high-distractor block). The impact of the direct carryover effects could not account for the slowing effects for RTs in distractor trials.

In general terms, performance was similar in the two types of mixture blocks. The only differences were that (1) RTs on no-distractor trials increased (high-distractor block > low-distractor block > pure no-distractor block) and (2) RTs on distractor trials tended to be faster as proportionally fewer trials occurred with singleton distractors (full-distractor block > high-distractor block > low-distractor block). These effects could be due to some form of strategic slowing of responses when singleton distractors are present on most trials or, alternatively, to negative position priming from singleton distractors across trials. However, it should be noted that the blocking factor of trials did not interact with the priming effects in all transitions in intertrial analyses. This suggests that the priming effects in the separate presentation blocks were held in the same degree even in the mixed presentation blocks.

In summary, the RTs to targets were not affected by the presence of the singleton distractors on the concurrent display. Also, the impact of the presence of singleton distractors in the directly preceding trials was insufficient to fully explain cross-dimensional interference effects originally obtained in separate no-distractor- and distractor-blocking presentation. RTs on the current trial were determined by the position priming (positive or negative priming in consecutive trials) and the context effect caused by strategic aspects of subjects. The context effect mainly affected the slowing of the baseline of RTs in both no-distractor and distractor trials.

GENERAL DISCUSSION

The results reported in this study demonstrate that positive and negative position priming could occur across successive trials in searching for targets with cross-dimensionally defined singleton distractors. Using in-

tertrial analyses, we showed that negative position priming occurred when targets on trial n fell at the locations of singleton distractors on trial $n - 1$. This negative carryover effect can slow performance across blocks of trials in which singleton distractors are presented in search tasks (Experiment 1). In Experiment 2, we equated such carryover effects across displays in which singleton distractors either were or were not present, by presenting mixtures of distractor and no-distractor trials. Under these conditions, cross-dimensional interference from the singleton distractors was eliminated. This suggests that the cross-dimensional interference effects revealed by the costs in RTs in the distractor trials over the no-distractor trials were not due to attentional capture to singleton distractors, solely driven by stimulus factors in the current trials, at least when a limited number of target and distractor locations were used.

Although we found no cross-dimensional interference when distractor trials were interleaved with no-distractor trials, in other reports cross-dimensional interference has appeared to be present under similar circumstances (Bacon & Egeth, 1994; Theeuwes, 1995). This suggests that within-trial interference may occur in addition to the across-trial effects we have observed, but the conditions of our study did not yield this. Previous studies have demonstrated that cross-dimensional interference varies as a function of the relative saliency of targets and distractors (Theeuwes, 1991, 1992). Consequently, it is possible that the differences we used were insufficient to produce within-trial interference (although they were sufficient to generate across-trial priming effects). A further factor could relate to positional uncertainty concerning the target. Other studies of cross-dimensional interference have used larger number of potential target positions (20 in Kumada, 1999; random positions along a virtual circle in Bacon & Egeth, 1994; Theeuwes, 1991, 1992). We used just four locations (see also Folk & Remington, 1998). It may be that subjects may be able to effect some form of top-down control over selection (eliminating within-trial interference), but this is limited to a fixed number of positions. This issue requires further research.

As was noted in the introduction, Folk and Remington (1998) have recently argued for dual factors' affecting interference from singleton distractors: one that is due to the capture of spatial attention (although only when distractors have attributes related to those of targets) and one that is nonspatial in nature. They attributed this nonspatial effect to *filtering costs* (Kahneman et al., 1983), a slowing of the deployment of spatial attention to an object without eliciting a shift in spatial attention itself. The nature of such filtering costs remains poorly understood, however. Our results have demonstrated an across-trials interference effect that is contingent on the spatial relations between current targets and the singleton distractors present on preceding trials. Negative position priming would be considered *nonspatial* within Folk and Remington's framework, since it is unrelated to the spatial relations between the target and the singleton distractor present on the same trial.

It is possible that negative position priming generates the filtering costs found even when distractors do not attract focal attention on a trial. For example, targets and distractors may compete with one another in a mutually inhibitory manner, to determine which stimulus is selected. The magnitude of inhibition may also be a function of the degree of competition. In order to select a target, singleton distractors that are attractive to attention may need to be strongly inhibited in this competition (Houghton et al., 1996; Tipper et al., 2000). The net result is a negative carryover effect for targets subsequently presented at the location of singleton distractors. Our data demonstrated that this form of inhibition can take place even when singleton distractors themselves are not subject to focal attention on a trial (as is evidenced by the absence of within-trial interference in Experiment 2). In our terms, there is inhibition through competition, rather than inhibition's being a consequence of the deployment and later withdrawal of focal attention from distractors. The failure to find evidence for distractors being attended also goes against cross-trial inhibition's being due to inhibition of return (Posner & Cohen, 1984). Our data demonstrated that inhibitory processing to singleton distractors could occur without any costs for selecting targets. This is consistent with recent studies, suggesting that singleton distractors may receive processing to some extent, using eye-movement measures (Theeuwes, Kramer, Hahn, & Irwin, 1998), probe detection tasks (Kim & Cave, 1999), and response compatibility tasks (Theeuwes, 1995; Theeuwes & Burger, 1998).

In Experiment 1, we found that negative position priming occurred at both locations on that side of fixation at which the singleton distractor had appeared. This suggests either that the inhibition was spatially spread or that it might be hemifield specified. Hemifield effects of spatial cuing on attention have been reported by Rizzolatti, Riggio, Dascola, and Umiltà (1987). In the present circumstances, hemifield effects might reflect inhibition of any tendency to orient attention to one side of space. In Experiment 2, there were again trends for inhibition at locations on the same side as that at which singleton distractors had appeared, although negative position priming was reliable only when targets fell at the location of the distractor. It will be important for future studies to determine the specificity of the negative position priming effect, to understand the underlying mechanism.

In apparent contrast to the negative carryover effects, we did find position specificity in positive priming, when targets fell at the same location across consecutive trials (see also Maljkovic & Nakayama, 1996). In Experiment 1, positive position priming also occurred with color targets, as well as with orientation targets (unlike the negative effects). This suggests that the two effects may have different causes. Positive priming may reflect increased activation in early visual representations produced by feedback during the process of target selection. This boosts the processing of all subsequent targets, whether they are weakly or highly salient (with both orientation and color here). Negative priming may reflect a later process, concerned with orient-

ing attention to one location or to one side of space. These proposals need to be validated by further research; for the present, our study is important for revealing a role of such priming mechanisms in cross-dimensional interference.

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