Exp Brain Res (2008) 185:175–188
DOI 10.1007/s00221-007-1141-7

RESEARCH ARTICLE

Searching for two feature singletons in the visual scene: the localized attentional interference effect

Ping Wei · Jianguo Lü · Hermann J. Müller · Xiaolin Zhou

Received: 28 January 2007 / Accepted: 14 September 2007 / Published online: 6 October 2007

Abstract The localized attentional interference (LAI) effect was investigated in a visual search task requiring participants to simultaneously monitor two spatially separated features from the same or different dimensions. In Experiment 1, the search type was blocked and targets were defined by fixed feature values in two dimensions (e.g., a yellow item and a circular item). In contrast, in Experiment 2, participants had to look for a color and a form singleton, with the exact feature values varying randomly across trials. In both experiments, reaction times (RTs) were generally slower when two features were CLOSE to, rather than DISTANT from, each other. Moreover, RTs to CLOSE stimuli increased as the search set size increased, while RTs to DISTANT stimuli were unaffected by set size. Experiment 3 also used a singleton search task, but with the two singletons defined either in different dimensions or in the same dimension. A larger interference effect for CLOSE, as compared to DISTANT, stimuli was found for cross-dimension than for intra-dimension targets. These findings suggest that neighboring items, irrespective of whether these items are from the same or different dimensions, interfere with each other in attentional selection, and that searching for two cross-dimension targets may engage a process of dimension switching to effectively solve the ambiguity of each item, especially when these items are close to each other.

Keywords Visual search · Feature search · Singleton search · Localized attentional interference · Dimension weighting

Introduction

It has been proposed that visual attentional selection operates by means of both the enhancement of the representations of selected objects (or locations) and the suppression of the representations of nearby distractors. There is a good deal of evidence suggesting that the focus of attention is surrounded by a "ring of suppression" within which items, whether they are task-relevant or -irrelevant, are inhibited (Braun and Sagi 1990; Caputo and Guerra 1998; Cave and Zimmerman 1997; Levi et al. 2002a, b; Mounts 2000a, b; Mounts and Gavett 2004; Mounts and Tomaselli 2005). Evidence for this notion of localized suppression or "localized attentional interference" (LAI) comes from experiments that use attention-capture, target-probe or two-target identification paradigms. In the attention-capture paradigm, participants are required to search for a specific target that is presented together with a visually salient distractor. It is generally found that the reaction times (RTs) to detect the target or to discriminate its identity are affected by the distance between the target and the distractor, with slower RTs when they are close to each other rather than far apart (Cave and Zimmerman 1997; Mounts 2000b; Mounts and Tomaselli 2005). In the target probe paradigm, participants are asked to make a discrimination

---

P. Wei · X. Zhou (✉)
Department of Psychology, Peking University,
Beijing 100871, China
e-mail: xz104@pku.edu.cn

J. Lü
Department of Psychology, Mianyang Normal College,
Sichuan 621000, China

H. J. Müller
Department of Psychology,
LMU München, 80802 Munich, Germany

regarding a singleton item and then to respond to a probe presented near the singleton's location (Hopfinger et al. 2006; Mounts 2000a). Probe discrimination sensitivity (in terms of a signal detection measure) is found to be poorer when the probe is close to the singleton location than when it is far away. In the two-target paradigm, participants' accuracy in identifying the two targets presented among a fixed number of distractors is found to be improved when the spatial separation between them increases (Bahcall and Kowler 1999; Cutzu and Tsotsos 2003; McCarley et al. 2004). Another line of evidence supporting the notion of local suppression stems from electrophysiological and functional brain imaging studies in which brain responses to a stimulus presented at the target location or a nearby location are measured. The event-related potentials (ERPs) are found to be enhanced when the probe is presented at the target location, and to be suppressed for probes within a narrow zone surrounding the target (Hopfinger et al. 2006; Heinze et al. 1994; Slotnick et al. 2002, 2003). A similar pattern has been reported for blood-oxygenation-level-dependent (BOLD) signals in extrastriate visual cortex (Bles et al. 2006; Kastner et al. 1998, 1999, 2001).

There are two accounts for this LAI effect: sensory-based ambiguity resolution (Luck et al. 1997) and space-based resource allocation (Bahcall and Kowler 1999). According to the ambiguity resolution account, the simultaneous processing of multiple objects, in particular, objects falling within the relatively large receptive fields of the same populations of neurons in extrastriate cortex, may lead to ambiguity in neural coding for individual objects. The visual system resolves this ambiguity by inhibiting items near the target. Without focused attention, neurons with large receptive fields, such as those in areas V4 and TE, could not code for the precise location of the features to which they are tuned. Single-cell recording studies in monkeys (e.g., Chelazzi et al. 1993; Moran and Desimone 1985; Reynolds et al. 1999) indicate that two stimuli presented at the same time within a neuron's receptive field are not processed independently; rather, they interact with each other in a mutually suppressive manner, competing for neural representation.

In contrast, the resource allocation account (Bahcall and Kowler 1999) assumes that the increased processing demands of the attended target are solved by "borrowing" attentional resources from neighboring regions. Enhanced processing at the attended location is achieved at the expense of the surrounding locations, with the processing of items at the latter locations being delayed or inhibited. Thus, visual attention may involve a reallocation of resources within a sub-region of the visual scene, without a net increase in the overall processing capacity. Note that the ambiguity resolution account is more directly informed by the neurophysiology of the visual system and the resource allocation account is based on cognitive hypotheses; thus they differ in terms of the level of explanation and may, ultimately, be reconcilable with each other.

Although there is strong evidence supporting the notion of local interference in visual attention, there are several questions that need further clarification. First, previous studies have typically not differentiated the visual dimensions of the critical stimuli. That is, effectively, they treated the two targets or the target and the distractor (or probe), such as letters or numerals, as single-dimension objects. It remains unclear whether the LAI effect is restricted to stimuli defined within the same visual dimension or whether the magnitude of the LAI effect is affected by the variation of dimensions for the two targets. According to the ambiguity resolution account, critical features from the color (e.g., red or green) and orientation dimensions (e.g., vertical or horizontal) may happen to be presented in overlapping receptive fields of neurons in extrastriate cortex. Thus, it is reasonable to assume that features from different dimensions interfere with each other in selective attention, although it is not clear whether this interference functions in the same way as intra-dimension interference. On the other hand, the original form of the resource allocation account does not specify whether "resource borrowing" takes place between features from different dimensions. Indeed, this account may have to be supplemented with the functional theories of visual search (e.g., Treisman and Gelade 1980; Treisman and Sato 1990; Müller et al. 1995, 2004; Wolfe 1994) if it meets issues concerning cross-dimension interference.

The second unresolved question concerns to what extent the LAI effect can be modulated by other factors such as the perceptual salience of the critical stimuli and the nature or difficulty of the task. In the attention-capture paradigm, the magnitude of the LAI effect has been found to be affected by the saliency of nearby distractors (Mounts 2000b; Mounts and Tomaselli 2005) and by the nature of the task to be performed (Braun and Julesz 1998; Braun and Sagi 1990, 1991; Mounts 2000a; Sagi and Julesz 1984): the LAI effect is more marked when the distractor is more salient and when the task requires more complex target discrimination rather than simple detection. However, it is not clear whether the density of stimuli within a given region—that is, the search set size—could affect the LAI effect. Mounts (2000a) manipulated the density in the target-probe paradigm and found that the LAI effect was affected only by the distance between the target and the probe, not by the item density in the search display. The latter finding is at variance with the predictions of both the ambiguity resolution and the resource allocation accounts. According to the former, more items falling within the receptive fields of the same populations of neurons would increase the ambiguity of neural coding, inducing stronger competition and interference among them. The resource allocation account would make the same prediction, as the difficulty of discerning the target from the distractors would increase when more items are placed in a fixed spatial region. With more distractors competing for limited attentional resources, there would be less spare resources in the surrounding region for the target to borrow from, inducing a stronger interference effect.

Given these open issues, this study re-examined the LAI effect in a visual search paradigm in which participants were asked to search for two simultaneously presented feature targets defined in separable dimensions: color and shape. The critical manipulation was whether the two features were spatially CLOSE to or DISTANT from each other in the two-feature search task. If the LAI works both with targets from the same dimension and with targets from different dimensions, one would expect to find slower RTs when the two features are CLOSE to, rather than DISTANT from, each other. Moreover, this pattern of interference effects could be modulated by the density of items in the search display: larger LAI effects would be obtained with an increased number of items within a given region. In Experiment 1, the type of search task and the distance between the two critical features were blocked, and the feature values of the targets were pre-specified and kept constant (e.g., search for a yellow target plus a circle target) for each block of trials. In Experiment 2, participants were required to perform singleton search with the precise featural values of the targets in the color and shape dimensions varying randomly across trials. Experiment 3 directly compared the LAI effect for cross-dimension targets with that for intra-dimension targets to examine whether additional processes in visual search contribute to the LAI effect. In all the experiments, the search set size (i.e., the item density) was varied randomly across trials within each experimental block.

Experiment 1

Experiment 1 comprised four critical types of search task: (1) search for a particular color in a block (single-feature search, color baseline); (2) search for a particular shape in a block (single-feature search, shape baseline); and search for two particular, spatially separate features, with the features being either (3) close to each other (two-feature search, CLOSE condition) or (4) far way from each other (two-feature search, DISTANT condition). The crucial question was whether we would observe slower RTs for CLOSE relative to DISTANT condition and whether the difference between the two conditions would increase with the increasing search set size.

Methods

Participants

Twenty undergraduate students from Peking University participated in Experiment 1. They were all right-handed and had normal or corrected-to-normal vision (including color vision). They gave their informed consent to take part in the experiment and were paid for their participation. The study was approved by the Academic Committee of the Department of Psychology, Peking University.

Stimuli and design

The experimental design consisted of three factors: search type, search set size, and target presence. The participants were instructed to search for certain target(s) within 5 × 5 display matrices which subtended $6.3^\circ \times 6.3^\circ$ of visual angle. There were four levels of search set size: 2, 6, 12, or 20 items. Target(s) were present in half of the trials, and absent in the other half.

An item in a display could be one of the four types: blue circle, blue square, yellow circle, and yellow square. In a given block, the target-defining features were pre-specified in advance. Table 1 lists all combinations of the target and distractor values. While the search type was blocked, the set size and target presence were varied randomly across trials within a block. On target-absent trials in the two baseline conditions, only the distractors were displayed. On target-absent trials in CLOSE and DISTANT conditions, half of the trials contained a color target but no shape target, and the other half a shape target but no color target. Only when the two targets were present simultaneously were the participants to make a positive response.

Each of the four search tasks comprised four blocks of stimuli, as specified in Table 1. Each block consisted of 64 trials with four levels of set size. The total 16 testing blocks were randomly presented to the participants, with the instruction about the target type presented at the beginning of each block. The mapping between stimulus and response hand was counterbalanced between participants.

Procedure

Presentation of the stimuli and recording of the responses were controlled by the Presentation software (http://nbs.neuro-bs.com/). At the start of each trial, a white fixation cross, measuring 0.20° of visual angle, appeared at the center of the black screen for 1,000 ms. A black screen of 100 ms was inserted 200 ms after the onset of the fixation marker, so that the cross appeared to flash briefly. This was to warn participants about the upcoming search display, which was presented for 500 ms. Items in each display were placed

Table 1 The stimuli used within each testing block in Experiment 1. Each search type has four blocks

Search type	Blocks	Instruction: search for	Target	Distractors
Color	1	A blue	Blue circle	Yellow circle
	2	A blue	Blue square	Yellow square
	3	A yellow	Yellow circle	Blue circle
	4	A yellow	Yellow square	Blue square
Shape	1	A circle	Blue circle	Blue square
	2	A circle	Yellow circle	Yellow square
	3	A square	Blue square	Blue circle
	4	A square	Yellow square	Yellow circle
CLOSE or DISTANT	1	A blue and a circle	A blue (square) and a (yellow) circle	Yellow square
	2	A blue and a square	A blue (circle) and a (yellow) square	Yellow circle
	3	A yellow and a circle	A yellow (square) and a (blue) circle	Blue square
	4	A yellow and a square	A yellow (circle) and a (blue) square	Blue circle

randomly at the 24 possible grid locations, with the fixation marker occupying the central position of the grid. Each item subtended 0.6° × 0.6° of visual angle. The viewing distance was held constant at 66 cm by using a chinrest. Participants were instructed to respond as quickly and as accurately as possible to the presence versus absence of the target(s). A blank screen was presented for 1,800 ms after the search display. Before the main experiment, each participant received four practice blocks of 20 trials for each type of search task.

Results

Incorrect responses were excluded from the analyses of RTs. Furthermore, RTs more than three standard deviations above or below the mean in each experimental condition were discarded as "outliers" (1.1% of responses in total). Mean RTs and response error percentages are reported in Table 2 for each experimental condition. Figure 1 depicts RTs in the CLOSE and DISTANT conditions relative to the averaged RTs in the two baseline conditions.

Preliminary data analyses had revealed no significant effect of set size on RTs in the baseline conditions (see Table 2). Therefore, the subsequent analyses of RTs in CLOSE and DISTANT conditions were based on the differential RTs relative to the averaged baseline conditions (see also Mounts 2000b).

A 2 (search type) × 4 (set size) × 2 (target presence) analysis of variance (ANOVA) revealed the following main effects to be (marginally) significant: set size, $F(3, 57) = 5.85$, $P = 0.001$, and search type, $F(1, 19) = 3.29$, $P = 0.08$. Importantly, the search type × target presence and the search type × set size interactions were also significant, $F(1, 19) = 3.87$, $P = 0.06$, and $F(3, 57) = 3.79$, $P < 0.05$.

To examine these interactions, the target-present and -absent RTs were analyzed by separate ANOVAs. For target-present RTs, the main effects of set size and of search type were significant, $F(3, 57) = 4.90$, $P < 0.005$, $F(1, 19) = 4.76$, $P < 0.05$, as was the search type × set size interaction, $F(3, 57) = 3.77$, $P < 0.05$. Further analyses showed that RTs increased with increasing set size for CLOSE condition, $F(3, 57) = 7.36$, $P < 0.001$, but did not vary as a function of set size for DISTANT condition, $F(3, 57) < 1$. Thus, the interference effect for CLOSE, relative to DISTANT, condition monotonically increased with increasing set size: 2, 19, 27, and 34 ms for set sizes 2, 6, 12, and 20 items, respectively. Planned *t*-tests comparing RTs between CLOSE and DISTANT conditions at different set sizes revealed the RT differences for 6-, 12-, and 20-item displays to be significant, $t(19) = 2.03$, $P = 0.056$, $t(19) = 2.29$, $P < 0.05$, and $t(19) = 2.76$, $P < 0.05$.

For target-absent trials, there was only a significant main effect of set size, $F(3, 57) = 2.80$, $P < 0.05$. Further analyses

Table 2 Mean reaction times (ms) and error percentages (in parentheses) in Experiments 1

Search type	Target present				Target absent			
	Set size				Set size			
	2	6	12	20	2	6	12	20
Color	405 (1.6)	408 (2.5)	420 (2.3)	419 (5.3)	451 (3.1)	434 (2.2)	431 (1.4)	426 (0.6)
Shape	450 (3.0)	455 (3.3)	456 (2.3)	473 (4.4)	489 (3.8)	488 (2.5)	499 (2.7)	503 (1.6)
CLOSE	521 (2.0)	544 (3.3)	562 (5.2)	575 (6.3)	566 (7.2)	571 (6.1)	567 (4.8)	570 (4.1)
DISTANT	519 (3.8)	525 (2.8)	534 (3.6)	541 (3.6)	555 (4.8)	568 (5.8)	556 (5.0)	552 (6.9)

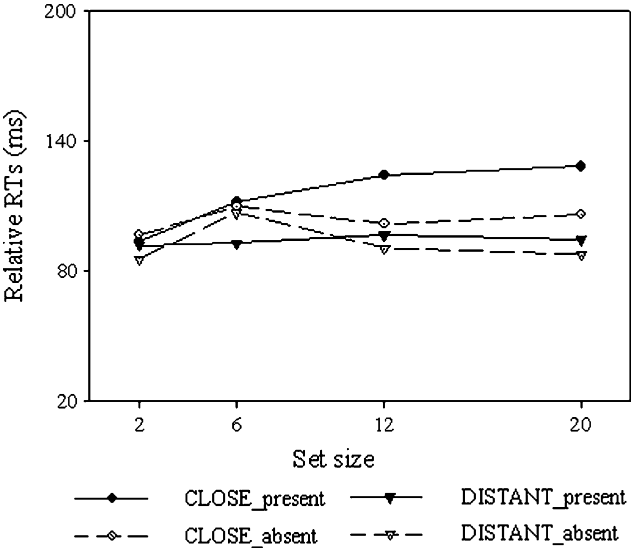

Fig. 1 RTs in CLOSE and DISTANT conditions relative to the averaged RTs of the target-present and the target-absent trials in the two baseline conditions in Experiment 1

revealed that RTs in CLOSE condition was not unaffected by set size, $F(3, 57) = 1.38$, $P > 0.1$. In contrast, RTs in DISTANT condition showed a set size effect, $F(3, 57) = 2.95$, $P < 0.05$, mainly due to RTs for six-item displays being slower compared to the other set sizes. Importantly, though, there was no significant difference between RTs in CLOSE and DISTANT conditions, $F(1, 19) = 1.60$, $P > 0.1$. This is not surprising given that, in both conditions, only one target was presented on "target-absent trials."

An ANOVA on the error rates, using a 2 (search type) × 4 (set size) × 2 (target presence) design, revealed only a significant main effect of target presence, $F(1, 19) = 14.38$, $P = 0.001$, and a significant three-way interaction, $F(3, 57) = 7.03$, $P < 0.001$. Separate follow-on ANOVAs were then performed for target-present and -absent trials (target miss and false alarm errors, respectively). For the miss rates, there was an significant interaction between search type and set size, $F(3, 57) = 3.20$, $P < 0.05$. Further analyses showed that the miss rates were unaffected by set size for CLOSE and DISTANT conditions, $F(3, 57) = 2.13$, $P > 0.1$, and $F(3, 57) = 2.12$, $P > 0.1$, respectively. Planned tests comparing the miss rates between CLOSE and DISTANT conditions at different set sizes revealed no significant differences for 2-, 6-, and 12-item displays, $t(19) < 1$, $t(19) < 1$, and $t(19) = 1.42$, $P > 0.1$, respectively, while for 20-item displays the miss rate was higher in CLOSE relative to DISTANT condition, $t(19) = 2.38$, $P < 0.05$.

For the false-alarm rates, there was also a significant interaction between set size and search type, $F(3, 57) = 3.47$, $P < 0.05$. Further analyses showed the false-alarm rates to be unaffected by set size in CLOSE condition, $F(3, 57) < 1$. In DISTANT condition, the false-alarm rates were affected by set size, $F(3, 57) = 3.43$, $P < 0.05$, with more false alarms being made with 20-item displays compared to smaller displays. However, the overall false alarm rates did not differ between CLOSE and DISTANT conditions, $F(1, 19) < 1$.

Discussion

Findings in Experiment 1 are consistent with the LAI hypothesis for spatial selective attention. When participants were required to search for two independent features from two different dimensions, RTs were slowed when the two targets were close to each other compared to when they were far apart. The magnitude of this interference effect increased as a function of set size. Specifically, while RTs to DISTANT targets were not affected by set size, RTs to CLOSE targets increased monotonically as the set size (the item density) increased. The error rates showed a similar pattern.

The interference revealed for CLOSE condition is consistent with both the ambiguity resolution account (Luck et al. 1997) and the resource allocation account (Bahcall and Kowler 1999). According to the former, features from different dimensions would compete for neural representation if these features fall within the receptive fields of the same populations of neurons in extrastriate cortex. Moreover, our results demonstrated that the strength of this interference is affected by the number of task-irrelevant distractors falling within the suppression ring. When no or only few distractors were presented (i.e., for set sizes of 2 or 6 items), there was little evidence of interference between the two targets in CLOSE, relative to DISTANT, condition. This may reflect the fact that, with low item density, the ambiguity in the neural coding for the targets and the surrounding distractors is not severe. When there are more distractors in the search display, the likelihood of distractors falling within the suppression ring is increased, producing greater ambiguity in the encoding of the targets. The reason for Mounts (2000b) failing to find an impact of set size (or item density) on the LAI effect is perhaps that the set size in his "low-density" condition was already very high (28 items).

According to the resource allocation account (Bahcall and Kowler 1999), processing of each target is solved by borrowing attentional resources from the neighboring region without net increasing of the overall resources. In the present visual search paradigm, how do the attentional resources reallocate over the search display? Wolfe's (1994) Guided Search 2.0 model suggests that, although each dimension computes its own saliency map providing information about "where" there is a feature difference signal, retrieving the exact "what" value of that salient signal requires focal attention to be directed to its location on the master map. Given that participants in Experiment 1 were asked to identify the exact value(s) of the target(s), they would have had to backtrack to the specific dimensional map to discern the possible targets after finding the peak signals on the master map, with focal attention consuming attentional resources. It is then reasonable to assume that, in DISTANT condition, the two peak signals did not interfere with each other because they could borrow enough resources in their respective sub-regions. However, when the two signals were CLOSE to each other, they may have caused interference by drawing upon attentional resources from the same region. In this way, the resource allocation account can also accommodate the influence of set size on the LAI effect. There are less spare attentional resources for the targets to borrow when there are more items in the search display, binding more attentional resources.

However, if participants are asked to simply respond to whether there are two singletons (defined in different dimensions) in the display, rather than responding to the exact feature values of the targets, they may detect the peak signals on the master map with no need to backtrack to specific dimensional maps. Mounts (2000a; see also Braun and Julesz 1998; Braun and Sagi 1990, 1991; Sagi and Julesz 1984) asked participants to identify the form of a singleton stimulus and then to make either a detection or a discrimination response to the subsequently presented probe. He observed an LAI effect for the discrimination task, but not for the detection task, suggesting that probe detection relies on pre-attentive mechanisms and is thus unaffected by the allocation of focal attention to the nearby objects. Assuming that counting signals on the master map or in a dimensional map makes no (or few) demands on focal attentional resources (at least within the subitizing range; see Found and Müller 1996), the resource allocation account would predict no difference between CLOSE and DISTANT conditions in the singleton detection task. In contrast, the ambiguity resolution account would still predict an LAI effect for CLOSE, relative to DISTANT, condition because, on this account, the manifestation of LAI effect is determined by whether or not the neuron populations coding for the two features have overlapping receptive fields. Experiment 2 was designed to examine the differential predictions between these two accounts by introducing responses that required detection of singletons, rather than discernment of their exact feature values.

Experiment 2

Methods

Participants

Eighteen undergraduate students from Peking University participated in Experiment 2. None of them had taken part in Experiment 1. They were all right handed and had normal or corrected-to-normal vision (including color vision). They gave their informed consent to take part in the experiment and were paid for their participation.

Stimuli and design

Like Experiment 1, Experiment 2 used a 4 (search type) × 4 (set size: 6, 10, 16, 20) × 2 (target present, absent) design. Search type was blocked, with two testing blocks for each type. For the two baseline and CLOSE and DISTANT conditions, the target(s) on a trial was (were) defined as one (or two) item(s) differing from the other items along one (or two) critical dimension(s). That is, the targets were defined as singletons whose exact feature values within the critical dimension(s) were variable across trials within a testing block. In the baseline conditions, participants were asked to search for a color or, respectively, a shape singleton in two blocks, with the task-irrelevant dimension (i.e., shape or, respectively, color) constant throughout a block. Participants were asked to discern the presence of two singletons from whatever dimensions in CLOSE and DISTANT conditions. The combinations of target and distractor values for each block are listed in Table 3.

There were two testing blocks for each search type, with 128 trials per block. Within each block, there were equal

Table 3 The stimuli used within each testing block in Experiment 2

Search type	Blocks	Instruction: search for	Target	Distractors
Color	1	A color singleton	Blue circle or yellow circle	Yellow circle or blue circle
	2	A color singleton	Blue square or yellow square	Yellow square or blue square
Shape	1	A shape singleton	Blue circle or blue square	Blue square or blue circle
	2	A shape singleton	Yellow circle or yellow square	Yellow square or yellow circle
CLOSE or DISTANT	1	Two singletons	A blue (square) and a (yellow) circle or a yellow (circle) and a (blue) square	Yellow square or blue circle
	2	Two singletons	A blue (circle) and a (yellow) square or a yellow (square) and a (blue) circle	Yellow circle or blue square

Each search type has two testing blocks

numbers of trials for the four levels of set size and for target presence/absence. All other methodological details were the same as in Experiment 1.

Results

Incorrect responses were excluded from the RT analysis. Furthermore, RTs more than three standard deviations above or below the mean in each experimental condition were discarded as "outliers" (0.9% of responses in total). Mean RTs and response error percentages are reported in Table 4 for each experimental condition. Figure 2 depicts the RTs in CLOSE and DISTANT conditions relative to the averaged RTs in the two baseline conditions.

A 2 (search type) × 4 (set size) × 2 (target presence) ANOVA on the RT data revealed a significant main effect of set size, *F*(3, 51) = 10.46, $P < 0.001$, but no main effect of search type, *F*(1, 17) = 3.03, $P = 0.1$, and target presence, *F*(1, 17) < 1. Importantly, the set size × target presence and the search type and set size interactions were significant, *F*(3, 51) = 2.45, $P = 0.074$, and *F*(3, 51) = 2.55, $P = 0.066$, respectively. That is, the RT differences between the search tasks varied according to search set size and target presence. This was further supported by the significant three-way interaction, *F*(3, 51) = 6.38, $P = 0.001$.

To analyze these interactions further, separate set size × search type ANOVAs were performed on the target-present and -absent RTs. For target-present trials, there was a significant main effect of set size, *F*(3, 51) = 4.57, $P < 0.01$, and a significant interaction between set size and search type, *F*(3, 51) = 8.75, $P < 0.001$. Further analyses revealed that, while RTs increased as a function of set size for CLOSE condition, *F*(3, 51) = 10.87, $P < 0.001$, they were unaffected by set size for DISTANT condition, *F*(3, 51) < 1. Planned tests comparing RTs between CLOSE and DISTANT conditions at the various set sizes revealed the differences to be marginally significant at set sizes 10 and 16 items (33 and 34 ms, respectively), *t*(17) = 1.91, $P = 0.07$; *t*(17) = 1.97, $P = 0.06$, and significant at set size 20 items (43 ms), *t*(17) = 2.28, $P < 0.05$. Thus, the interference effect for CLOSE condition, relative to DISTANT condition, increased monotonically with increasing set size.

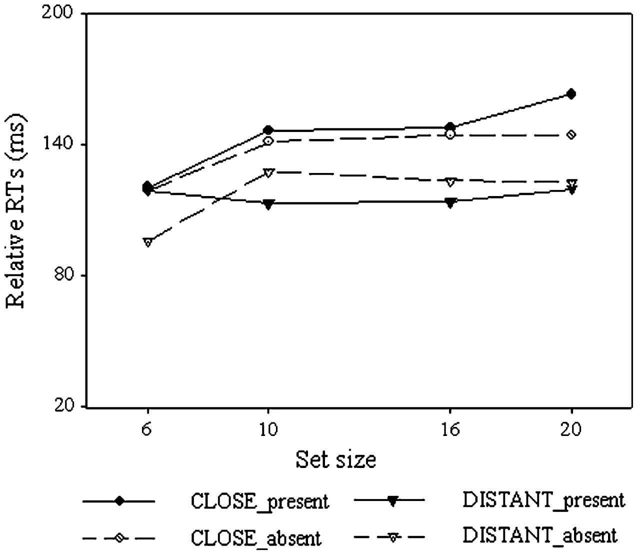

Fig. 2 RTs in CLOSE and DISTANT conditions relative to the averaged RTs of the target-present and the target-absent trials in the two baseline conditions in Experiment 2

For target-absent trials, there was only a significant main effect of set size, *F*(3, 51) = 9.66, $P < 0.001$. Further analyses showed that RTs increased as a function of set size for both conditions—CLOSE: *F*(3, 51) = 4.55, $P < 0.05$, and DISTANT: *F*(3, 51) = 7.23, $P < 0.001$. The comparison between CLOSE and DISTANT conditions did not reach significance, *F*(1, 17) = 2.47, $P > 0.1$, although the overall RT difference between them was about 20 ms.

A 2 (search type) × 4 (set size) × 2 (target presence) ANOVA for the error rates revealed a significant main effect of search type, *F*(1, 17) = 9.64, $P < 0.01$. The two-way interaction between set size and target presence was also significant, *F*(3, 51) = 6.77, $P = 0.001$, as was the three-way interaction, *F*(3, 51) = 4.56, $P < 0.01$. Separate two-way ANOVAs were then performed for the target miss (target-present trials) and false alarm (target-absent trials) errors. For target misses, there were significant main effects of set size, *F*(3, 51) = 5.18, $P < 0.005$, and of search type, *F*(1, 17) = 6.24, $P < 0.05$, and a significant search type × set size interaction, *F*(3, 51) = 3.53, $P < 0.05$. Further analyses showed that the miss rate increased as a

Table 4 Mean reaction times (ms) and error percentages (in parentheses) in Experiments 2

Search type	Target present				Target absent			
	Set size				Set size			
	6	10	16	20	6	10	16	20
Color	415 (2.6)	413 (1.0)	432 (3.0)	440 (2.8)	449 (2.1)	444 (2.1)	449 (1.6)	447 (1.2)
Shape	455 (2.1)	467 (4.3)	470 (3.3)	474 (3.5)	491 (1.9)	511 (3.8)	521 (3.3)	513 (2.6)
CLOSE	555 (5.4)	581 (4.7)	582 (7.1)	598 (11.3)	589 (9.4)	611 (9.7)	615 (8.5)	615 (7.6)
DISTANT	554 (6.4)	548 (3.3)	549 (5.7)	555 (5.0)	566 (5.4)	598 (7.6)	594 (8.7)	593 (5.7)

function of set size for CLOSE condition, $F(3, 51) = 9.46$, $P < 0.001$, but was unaffected by the set size for DISTANT condition, $F(3, 51) = 1.17$, $P > 0.1$. Planned tests comparing the miss rates between CLOSE and DISTANT conditions at the various sizes showed that, while the differences at set sizes 6, 10, and 16 items were not significant, $t(17) < 1$, $t(17) = 1.19$, $P > 0.1$, and $t(17) < 1$, respectively, the miss rate at set size 20 items was larger in CLOSE, relative to DISTANT, condition, $t(17) = 3.65$, $P < 0.05$.

For the false alarms, there was only a significant main effect of search type, $F(1, 17) = 4.90$, $P < 0.05$. Further analyses showed that the false alarm rates did not vary with set size for both CLOSE and DISTANT condition, $F(3, 51) = 1.39$, $P > 0.1$, and, respectively, $F(3, 51) = 2.21$, $P = 0.1$. Planned tests comparing the false alarm rates between CLOSE and DISTANT conditions at the various sizes showed that, while the differences were not significant at set sizes 10, 16, and 20 items, $t(17) = 1.62$, $P > 0.1$, $t(17) < 1$, and $t(17) = 1.61$, $P > 0.1$, respectively, the miss rate was larger in CLOSE relative to DISTANT condition at six-item displays, $t(17) = 2.57$, $P < 0.05$.

Discussion

The pattern of effects in Experiment 2 was similar to Experiment 1. Relative to the baseline conditions, RTs to CLOSE targets increased with set size, whereas RTs to DISTANT targets remained relatively constant. Moreover, when set size was relatively large, RTs were slower to CLOSE than to DISTANT targets.

These findings are most consistent with the ambiguity resolution account, which attributes the LAI effect with CLOSE targets to the competition among neural feature representations by neurons with overlapping receptive fields. In contrast, the resource allocation account in the present form would have difficulties in accommodating the findings if detection, as previous studies suggested, is not subject to the limitation of attentional resources (Braun and Julesz 1998; Braun and Sagi 1990, 1991; Sagi and Julesz 1984; Mounts 2000a).

To keep the theoretical thrust of the resource allocation account and to accommodate the discrepant findings between Experiment 2 and some of the previous studies, one might suggest that the complex two-singleton search (as required in Experiment 2) is not simply a doubling of one-singleton detection (as in Mounts 2000a) and the borrowing of attentional resources does happen in this case. First, it is possible that counting a limited number (≤ 4) of saliency peaks on the master map can be accomplished without focal attention, as in subitizing. However, one may need to switch from one-dimensional map to the other to effectively count saliency peaks in separate dimensions. This is suggested by Found and Müller (1996, Experiment 3), who observed that counting peaks is harder when these are produced by signals from two separate dimensions, as compared with just one dimension. Second, since saliency computations are rough and fast, the peak of the overall-saliency (master map) signal may be somewhere in-between the dimension-specific signals, with two close signals actually giving rise to one peak on the master map in a center-of-gravity manner (e.g., Findlay et al. 1993; Zhou et al. 2006). This idea could be a manifestation at the cognitive level of the ambiguous neural coding suggested by Luck et al. (1997). Previous work (e.g., Krummenacher et al. 2001, 2002) has provided evidence that dimension-specific saliency signals from separate dimensions are integrated into master map signals in a spatially scaled manner; that is, there is integration of signals from the same as well as neighboring locations, but not distant locations. Thus, if only one peak is initially found with CLOSE targets, the system needs to check whether there are actually two underlying peaks originating from separate dimensional maps. This checking is time-consuming and may involve sequential weighting of one and then the other dimension to isolate two underlying peaks. In contrast, participants can immediately make a positive response if two (master map) peaks are found, incurring no additional costs with DISTANT targets, whose dimension-specific signals are not integrated into one master map signal owing to their large spatial separation. By combining these two possible processes, the resource allocation account could also explain the LAI effect observed in Experiment 2.

Experiment 3

The ambiguity resolution account does not explicitly address whether the potential dimension switching processes contribute to the LAI effect; hence, it makes no explicit prediction concerning how the LAI would vary as a function of whether the two singleton targets are from the same or from different dimensions. On the other hand, the extended resource allocation account outlined above would predict a larger LAI effect for cross-dimension than for intra-dimension targets. Experiment 3 was designed to examine this issue by comparing the LAI effects between two types of singleton targets: cross-dimension targets (e.g., a yellow and a square item), and intra-dimension targets (e.g., a yellow and a blue item).

Methods

Participants

Twenty undergraduate students from Peking University, none of whom were tested for the previous experiments, took part in Experiment 3. They were all right handed and had normal or corrected-to-normal vision. They gave their informed consent to take part in the experiment and were paid for their participation.

Stimuli and design

Experiment 3 used a 2 (target dimension) × 2 (search type) × 4 (set size) × 2 (target presence) design, with participants being instructed to perform the two-singleton search. Two singleton targets were either from the same dimension or from different dimensions, and they were either CLOSE or DISTANT; the search set size was 6, 10, 16, or 20 items, and the targets were either both present or only one was present. In addition, there were one-target color singleton and shape singleton search conditions which served as baselines for the two-target CLOSE and DISTANT conditions. The combinations of target and distractors in each block are illustrated in Table 5. In the baseline conditions, participants were asked to search for a color or, respectively, a shape singleton. In CLOSE and DISTANT conditions, participants were instructed to search for two singletons from whatever dimensions. Cross-dimension target trials were mixed with intra-dimension target trials; the intra-dimension trials consisted of displays with either two color targets or two shape targets (each 50% of the trials).

The search type was blocked, with three testing blocks for each search type. Testing blocks consisted of either 96 trials (one-target search baselines) or 192 trials (two-target CLOSE and DISTANT conditions). Within each block, there were equal numbers of trials for the four levels of set size and for target presence/absence. All other methodological details were the same as in Experiment 2.

Results

Incorrect responses were excluded from the RT analysis, and RTs more than three standard deviations above or below the mean in each experimental condition were discarded as “outliers” (0.9% of responses in total). Mean RTs and response error percentages are reported in Table 6 for each experimental condition and Fig. 3 depicts the RTs for CLOSE and DISTANT conditions relative to the averaged RTs in the two baseline conditions.

A 2 (cross- versus intra-dimension) × 2 (CLOSE versus DISTANT) × 4 (set size) × 2 (target presence) ANOVA on the RT data revealed significant main effects of target presence, $F(1, 19) = 49.08$, $P < 0.001$, search type, $F(1, 19) = 32.23$, $P < 0.001$, and target dimension, $F(1, 19) = 27.11$, $P < 0.001$, but no main effect of search set size, $F(3, 57) = 2.14$, $P > 0.1$. Importantly, the target presence × search type and the target presence × dimension interactions were significant, $F(1, 19) = 4.48$, $P < 0.05$, and $F(1, 19) = 30.37$, $P < 0.001$, respectively. That is, the RT differences between CLOSE and DISTANT conditions and between the intra- and cross-dimension conditions varied according to whether or not the two targets

Table 5 The stimuli used within each testing block in Experiment 3

Search type	Blocks	Instruction: search for	Target	Distractors
Color	1	A color singleton	Blue circle or yellow circle	Yellow circle or purple circle
	2	A color singleton	Yellow square or purple square	Purple square or blue square
	3	A color singleton	Purple triangle or blue triangle	Blue triangle or yellow triangle
Shape	1	A shape singleton	Blue circle or blue square	Blue square or blue triangle
	2	A shape singleton	Yellow square or yellow triangle	Yellow triangle or yellow circle
	3	A shape singleton	Purple triangle or purple circle	Purple circle or square
Close or distant	1	Two singletons	A blue (square) and a (yellow) circle	Yellow square
			A yellow (circle) and a (blue) square	Blue circle
			A blue (circle) and a yellow (circle)	Purple circle
			A (blue) circle and a (blue) square	Blue triangle
	2	Two singletons	A yellow (triangle) and a (purple) square	Purple triangle
			A purple (square) and a (yellow) triangle	Yellow square
			A yellow (square) and a purple (square)	Blue square
			A (yellow) square and a (yellow) triangle	Yellow circle
	3	Two singletons	A purple (circle) and a (blue) triangle	Blue circle
			A blue (triangle) and a (purple) circle	Purple triangle
			A purple (triangle) and a blue (triangle)	Yellow triangle
			A (purple) triangle and a (purple) circle	Purple square

Each search type has three testing blocks

Table 6 Mean reaction times (ms) and error percentages (in parentheses) in Experiments 3

Search type	Target present				Target absent			
	Set size				Set size			
	6	10	16	20	6	10	16	20
Color	478 (2.8)	487 (2.6)	489 (5.1)	479 (4.0)	516 (2.2)	510 (3.2)	509 (2.8)	506 (2.8)
Shape	574 (7.2)	570 (8.6)	564 (5.0)	571 (5.8)	585 (5.7)	604 (6.8)	616 (6.3)	608 (4.9)
CLOSE_cross	652 (8.8)	651 (7.1)	650 (8.8)	655 (10.7)	718 (16.8)	727 (17.2)	733 (16.9)	726 (12.2)
CLOSE_intra	623 (5.6)	609 (8.3)	616 (8.5)	629 (6.8)	714 (17.8)	721 (15.9)	728 (15.8)	725 (12.6)
DISTANT_cross	599 (5.7)	593 (2.5)	595 (6.8)	596 (5.8)	705 (15.4)	697 (14.0)	695 (12.9)	689 (11.1)
DISTANT_intra	590 (6.8)	578 (3.2)	583 (6.1)	587 (6.3)	700 (14.3)	694 (14.7)	695 (13.3)	687 (10.7)

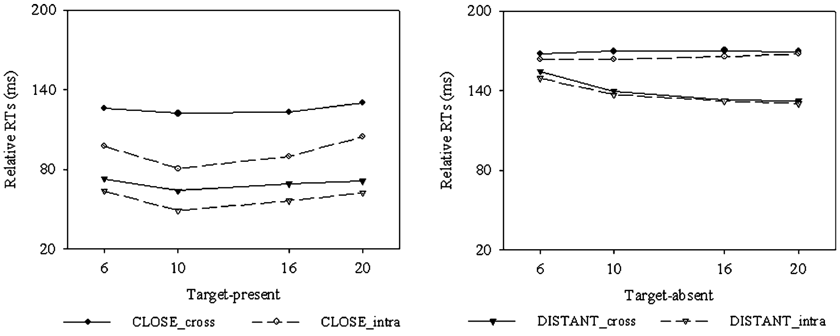

Fig. 3 RTs in CLOSE_cross, CLOSE_intra, DISTANT_cross, and DISTANT_intra conditions relative to the averaged RTs in the two baseline conditions in Experiment 3

were present. This was further supported by the significant three-way interaction between target presence, search type, and target dimension, $F(1, 19) = 10.54$, $P < 0.005$.

To analyze the interactions further, separate target dimension × set size × search type ANOVAs were performed for the target-present and -absent trials. For target-present trials, there was a main effect of search type, $F(1, 19) = 38.59$, $P < 0.001$, with longer RTs in CLOSE compared to DISTANT condition (109 ms vs. 64 ms). Importantly, there was also a significant main effect of dimension, $F(1, 19) = 29.21$, $P < 0.001$, with longer RTs for cross-dimension than for intra-dimension targets (97 ms vs. 75 ms). The main effect of set size was not significant, $F(3, 57) = 2.18$, $P > 0.1$, suggesting that RTs did not vary according to set sizes. The search type × dimension interaction was significant, $F(1, 19) = 18.60$, $P < 0.001$, due to the RT differences between CLOSE and DISTANT conditions being larger for cross-dimension targets (125 ms vs. 69 ms) than for intra-dimension targets (93 ms vs. 58 ms). Detailed tests showed that each of these differences was significant ($P < 0.05$).

For target-absent trials, there was a main effect of search type, $F(1, 19) = 12.90$, $P < 0.005$, with longer RTs in CLOSE than in DISTANT (167 ms vs. 139 ms) condition. Not surprisingly, the main effect of dimension was not significant, $F(1, 19) < 1$, given that search display contained only one target on target-absent trials and such trials did not differ between the cross- and intra-dimension conditions. The search type × set size interaction was significant, $F(3, 57) = 2.86$, $P < 0.05$, with the RT differences between CLOSE and DISTANT conditions increasing over set size.

A 2 (target dimension) × 4 (set size) × 2 (search type) × 2 (target presence) ANOVA on the error rates revealed a main effect of target presence, $F(1, 19) = 42.90$, $P < 0.001$, with more errors committed on target-absent compared to target-present trials (14.5% vs. 6.7%), and a main effect of search type, $F(1, 19) = 16.14$, $P = 0.001$, with more errors in CLOSE than in DISTANT condition (11.8% vs. 9.4%). None of the other main or interaction effects were significant—except for the four-way interaction, $F(3, 57) = 4.69$, $P = 0.005$. As can be seen from Table 6, this interaction was caused mainly by the unpredicted lower error rates for target-present trials in the ten-item display in DISTANT condition.

Discussion

The overall pattern of effects in Experiment 3 was similar to Experiment 2, except that the LAI effect did not increase as a function of set size. At all set sizes, RTs were slower to CLOSE as compared to DISTANT targets; moreover, RTs were generally slower to cross-dimension as compared to intra-dimension targets. Importantly, the RT differences between CLOSE and DISTANT conditions (i.e., the LAI effects) were larger for cross-dimension (125 ms vs. 69 ms) than for intra-dimension targets (93 ms vs. 58 ms). These findings are consistent with the hypothesis that the LAI effect is modulated by the distance between the two targets and by switch of dimensions when searching for two singletons simultaneously.

Without explicit assumptions about the possible differences between cross- and intra-dimension targets, both the ambiguity resolution (Luck et al. 1997) and the resource allocation accounts (Bahcall and Kowler 1999) met difficulties in explaining the above data pattern. Although these two accounts could be revised in different ways to deal with the new findings, our preferred solution is to appeal to the dimension-weighting account (Krummenacher et al. 2001, 2002; Müller et al. 1995). DISTANT targets produce two spatially separated saliency peaks on the master map which can be counted easily, so that there is little extra cost for cross-dimension relative to intra-dimension targets (69 ms vs. 58 ms). In contrast, CLOSE targets will tend to produce one (more flattish) saliency peak, so additional processing is needed to determine whether there is really just one underlying dimension-specific saliency signal (responding as target absent) or whether there are two signals (responding as target present). This would impair performance with both intra-dimension and cross-dimension targets. However, as argued below, with cross-dimension targets, as compared to intra-dimension targets, there would be a stronger tendency for fusing separate dimension-specific saliency signals into one overall-saliency peak (Krummenacher et al. 2002), increasing the demand for disambiguation.

Specifically, the reason for the stronger fusion of separate dimension-specific saliency signals into one overall-saliency peak is that the regional feature contrast would be greater for each cross-dimension target, than for each intra-dimension target. Suppose there are four items in a restricted region: two blue squares as distractors, and a blue circle and a yellow square as cross-dimension targets—or a blue circle and a blue triangle as intra-dimension targets. For a cross-dimension trial, one of the targets (e.g., the blue circle) accrues one feature contrast value by differing from the other target (yellow square) along the color dimension plus three values by differing from the two distractors and the other target along the shape dimension; the saliency of the other target would be derived in an analogous manner. For an intra-dimension trial, however, none of the targets obtains a feature contrast value along the color dimension while they accrue only three values by differing from the two distractors and the other target (blue triangle) along the shape dimension. Thus, as compared to intra-dimension condition, the two stronger peaks in the cross-dimension targets fused more and caused more ambiguity.

To resolve the ensuing ambiguity, backtracking to the source dimension(s) would be required, which may be guided by the pooled activity within dimension-specific saliency maps; that is, dimension which exhibits the highest pooled activity will be checked with priority (Müller et al. 1995). This will rapidly resolve the ambiguity for intra-dimension targets, as the critical dimension is checked immediately, yielding a count of two saliency signals (target present). In contrast, with cross-dimension targets, only one saliency signal is counted in whatever dimension being checked first. In order to discern the presence of a second target, checking must switch to the other dimension (Found and Müller 1996). Thus, the above account along the lines of dimension weighting would be consistent with the ambiguity resolution account of Luck et al. (1997), while providing an explicit mechanism by which intra- and cross-dimensional ambiguity would be resolved.

Experiment 3 did not find the LAI effect to be modulated by set size, inconsistent with Experiments 1 and 2. This may be due to the fact that the targets in CLOSE and DISTANT trial blocks in Experiment 3 were more variable (with randomly presented cross- and intra-dimension trials) than in Experiment 2, and this increased the overall task difficulty, as evidenced by the longer overall RTs in Experiment 3 compared to Experiment 2 (661 ms vs. 581 ms). The impact of set size on the LAI effect may be eliminated in a difficult task.

General discussion

The main findings of the three experiments can be summarized as follows. When participants were required to search for two feature targets concurrently, whether they had to discriminate the exact target-defining features (Experiment 1) or to just detect the singletons' presence (Experiments 2 and 3), RTs were generally slower when the two targets were CLOSE to each other than when they were DISTANT. Moreover, in Experiments 1 and 2, while RTs to DISTANT targets did not vary as a function of search set size, RTs to CLOSE targets increased as the set size increased. As a result, the differences in RTs between CLOSE and DISTANT conditions (i.e., the LAI effects) grew larger with increasing set size. Furthermore, Experiment 3 showed that the RT disadvantage for CLOSE relative to DISTANT conditions (i.e., the LAI effect) was larger when the two targets were from different dimensions, as compared to the same dimension.

The cross-dimension interference

This study demonstrates that the LAI effect is observed with any feature singletons close to each other, whether these features are defined in the same dimension or in different dimensions. With additional assumptions borrowed from the functional theories of visual search (e.g., Müller et al. 1995, 2004; Wolfe 1994), both the ambiguity resolution (Luck et al. 1997) and the resource allocation accounts (Bahcall and Kowler 1999) can accommodate these findings. Moreover, our results show that RTs to cross-dimension targets are longer than intra-dimension targets, suggesting a role of dimension switching in the two-singleton target search.

As discussed in Experiment 3, this dimension switching process, which consumes attentional resources, has a bigger impact upon the processing of CLOSE targets than upon the processing of DISTANT targets. Further evidence for this dimension switching and checking process is provided by the target-absent RTs in CLOSE and DISTANT conditions. Recall that, on target-absent trials in these conditions, only one feature singleton was presented. Thus, in order to give a negative ("target-absent") response, participants must differentiate the presence of only one singleton in the display from that of two singletons (in which case a positive, "target-present" response would have to be made). Assuming that CLOSE singletons may be integrated into one overall-saliency peak, further checking of dimension-specific saliency maps would be required not only to determine whether two such signals are actually present, but also to ascertain that there is a signal in only one dimension. This would predict negative RTs to be slower in CLOSE than in DISTANT condition, since the search type was blocked. Indeed, this prediction was confirmed by the data from all the three experiments. An ANOVA of the target-absent RTs, with the factors of experiment, search type, and set size, revealed a significant main effect of search type, $F(1, 56) = 12.70$, $P = 0.001$. Target-absent RTs (relative to the baseline conditions) were slower for CLOSE than for DISTANT condition (137 ms vs. 117 ms). This is equivalent to observers setting different thresholds for target-absent decisions between CLOSE and DISTANT conditions (e.g., see Chun and Wolfe 1996). That is, in CLOSE condition blocks, participants may actively adjust the threshold in deciding whether another target was present in the suppression ring. A higher threshold would prolong RTs not only on target-present trials, but also on target-absent trials, resulting in an interference effect relative to DISTANT condition.

Moreover, previous studies of attentional capture have demonstrated that the cross-dimension interference effect between two singletons is affected by the general bottom-up perceptual saliency between dimensions, with color normally being more salient than shape (Theeuwes 1991, 1992; Wei and Zhou 2006). Given that the RTs were faster in the color relative to the shape baseline task in all three experiments (see Tables 2, 4, 6), it is possible that the LAI effects observed in this study resulted mainly from the interference of the color singleton upon the shape singleton. Although we could not directly examine this possibility for the present data, this suggestion would be consistent with Mounts and Tomaselli (2005) who reported that a more salient distractor produces a stronger interference effect on a nearby target. Further studies are necessary to investigate the interaction between top-down task set and the relative bottom-up salience of various dimensions in determining the magnitude of the LAI effect in the two-singleton target search task.

The set size effect

Another new finding of this study was that the slow-down of RTs to CLOSE, relative to DISTANT targets, becomes more severe as the number of items in the search display (i.e., the item density) increases (at least with relatively easy searches, as in Experiments 1 and 2). This finding could be explained by existing accounts of the LAI effect. According to the ambiguity resolution account (Luck et al. 1997), when multiple items are presented in the receptive fields of same populations of neurons, the neural coding for each item becomes ambiguous. The primary computational role of selective attention is to resolve this ambiguity. In the present experiments, the greater the number of display items (within a given matrix), the higher the probability of more items being presented in the vicinity of the target. This would increase the ambiguity in the neural coding of the target, resulting in stronger interference. Why, then, would the increased number of distractors in DISTANT condition not affect the RTs to the two targets? Luck et al. (1997) suggested that the strength of competition between neural encodings of nearby items is regulated by both the top-down task set, which specifies the search-relevant target features, and the relative bottom-up saliency between the target and distractors. For CLOSE condition, the competition between the two salient targets is strong and the ambiguity in the neural encoding of the targets is increased by any extra distractors nearby. In contrast, for DISTANT condition, the two targets are encoded by separate populations of neurons, so that each target receives higher top-down priority than other items in neural encoding within its region. Additional distractors nearby would have little impact upon this encoding and the RTs to the targets.

The resource allocation account (Bahcall and Kowler 1999) hypothesizes a fixed-size pool of processing resources. The processing of the target at the attended location has to be accomplished by borrowing attentional resources from the surrounding region, resulting in a deficit in processing other items falling within that region. Although it is not clear how "attentional resources" are to be conceptualized precisely, one could draw upon the perceptual load theory of selective attention (see Lavie 2005, for a recent review) according to which processing multiple items in a display would consume more attentional resources and, thus, leave fewer resources available for a particular target. When the set size is small, there would be enough spare attentional resources to process the targets, whether the targets are CLOSE to or DISTANT from each other, so that the RTs would be comparable for CLOSE and DISTANT conditions. However, when the set size is large, there would be few spare attentional resources available for the processing of each target, which has to borrow resources from the neighboring region. If the two targets are close to each other, they may cause interference by drawing upon limited attentional resources from the same region, leading to the delay in processing the two targets.

However, the above two accounts seem to be more descriptive rather than explanatory in relation to the set size effect. Perhaps a more "mechanistic" account may be derived from saliency-based models such as Guided Search (Wolfe 1994), according to which feature contrast values would be computed not only for the targets, but also, in parallel, for the distractors. The saliency value of a distractor, signaling the extent to which it differs from other items in its vicinity, would be higher if there are two targets, rather than just one, within a narrow spatial region. As a result, sparse distractors within a given region would have a disproportionately large effect in diffusing the targets' saliency values in CLOSE condition, compared with DISTANT condition. However, this effect would subside as the number of distractors grows larger, depressing the saliency value of each identical distractor within the region. Consistent with this argument, in this study the interference produced by the distractors in CLOSE condition appeared to exhibit an asymptotic growth.

Conclusion

To conclude, by asking participants to search for two feature targets concurrently and by varying the distance between the two targets, the present study demonstrated that RTs were slower when the two targets were close to each other than when they were far apart. This interference effect was more marked for two targets from different dimensions than for targets from the same dimension. Furthermore, the interference with neighboring stimuli increased as the search set size increased, when the search task was relatively easy. Both the ambiguity resolution and the resource allocation accounts of the LAI effect have to be supplemented with functional theories of visual search to give a complete explanation of the data we observed.

Acknowledgments This study was supported by grants from the Natural Science Foundation of China (30470569, 60435010, and 30770712) to Xiaolin Zhou and by Germany DFG Research Group (FOR 480) and CoTeSys Excellence Cluster (142) grants to Hermann Müller. We thank two anonymous reviewers for their constructive comments on the earlier versions of the paper. Electronic mail concerning this study should be addressed to Dr. Xiaolin Zhou, xz104@pku.edu.cn.

References

Bahcall DO, Kowler E (1999) Attentional interference at small spatial separations. Vision Res 39:71–86

Bles M, Schwarzbach J, Weerd PD, Goebel R, Jansma BM (2006) Receptive field size-dependent attention effects in simultaneously presented stimulus displays. Neuroimage 30:506–511

Braun J, Julesz B (1998) Withdrawing attention at little or no cost: detection and discrimination tasks. Percept Psychophys 60:1–23

Braun J, Sagi D (1990) Vision outside the focus of attention. Percept Psychophys 48:45–48

Braun J, Sagi D (1991) Texture-based tasks are little affected by a second task which requires peripheral or central attentive fixation. Perception 20:483–500

Caputo G, Guerra S (1998) Attentional selection by distractor suppression. Vision Res 38:669–689

Cave KR, Zimmerman JM (1997) Flexibility in spatial attention before and after practise. Psychol Sci 8:399–403

Chelazzi L, Miler EK, Duncan J, Desimone R (1993) A neural basis for visual search in inferior temporal cortex. Nature 363:345–347

Chun MM, Wolfe JM (1996) Just say no: how are visual searched terminated when there is no target present? Cognit Psychol 30:39–78

Cutzu F, Tsotsos JK (2003) The selective tuning model of attention: psychophysical evidence for a suppressive annulus around an attended item. Vision Res 43:205–219

Found A, Müller HJ (1996) Searching for features across dimensions: evidence for a dimensional weighting account. Percept Psychophys 58:88–101

Findlay JM, Brogan D, Wenbanshith MG (1993) The spatial signal for saccadic eye-movements emphasizes visual boundaries. Percept Psychophys 53:633–641

Heinze HJ, Luck SJ, Muente TF, Gös A, Mangun GR, Hillyard SA (1994) Attention to adjacent and separate positions in space: an electrophysiological analysis. Percept Psychophys 56:42–52

Hopfinger JM, Boehler CN, Luck SJ, Tsotsos JK, Heinze HJ, Schoenfeld MA (2006) Direct neurophysiological evidence for spatial suppression surrounding the focus of attention in vision. Proc Natl Acad Sci USA 103:1053–1058

Kastner S, De Weerd P, Desimone R, Ungerleider L (1998) Mechanisms of directed attention in the human extrastriate cortex as revealed by functional MRI. Science 282:108–111

Kastner S, De Weerd P, Pinsk MA, Elizondo MI, Desimone R, Ungerleider L (2001) Modulation of sensory suppression: implications for receptive field sizes in the human visual cortex. J Neurophysiol 86:1398–1411

Kastner S, Pinsk MA, De Weerd P, Desimone R, Ungerleider L (1999) Increased activity in human visual cortex during directed attention in the absence of visual stimulation. Neuron 22:751–761

Krummenacher J, Müller HJ, Heller D (2001) Visual search for dimensionally redundant pop-out targets: evidence for parallel-coactive processing of dimensions. Percept Psychophys 63:907–917

Krummenacher J, Müller HJ, Heller D (2002) Visual search for dimensionally redundant pop-out targets: parallel-coactive processing of dimensions is location-specific. J Exp Psychol Hum Percept Perform 28:1303–1322

Lavie N (2005) Distracted and confused?: selective attention under load. Trends Cogn Sci 9:75–82

Levi DM, Hariharan S, Klein SA (2002a) Suppressive and facilitatory spatial interactions in peripheral vision: peripheral crowding is neither size invariant nor simple contrast masking. J Vision 2:167–177

Levi DM, Klein SA, Hariharan S (2002b) Suppressive and facilitatory spatial interactions in foveal vision: foveal crowding is simple contrast masking. J Vision 2:140–166

Luck SJ, Girelli M, McDermott MT, Ford MA (1997) Bridging the gap between monkey neurophysiology and human perception: an ambiguity resolution theory of visual selective attention. Cognit Psychol 33:64–78

McCarley JS, Mounts JW, Kramer AF (2004) Age-related differences in localized attentional interference. Psychol Aging 19:203–210

Moran J, Desimone R (1985) Selective attention gates visual processing in the extrastriate cortex. Science 229:782–784

Mounts JW (2000a) Evidence for suppressive mechanisms in attentional selection: feature singletons produce inhibitory surrounds. Percept Psychophys 62:969–983

Mounts JW (2000b) Attentional capture by abrupt onsets and feature singletons produce inhibitory surrounds. Percept Psychophys 62:1485–1493

Mounts JW, Gavett BE (2004) The role of salience in localized attentional interference. Vision Res 44:1575–1588

Mounts JW, Tomaselli RG (2005) Competition for representation is mediated by relative attentional salience. Acta Psychol 18:261–275

Müller HJ, Heller D, Ziegler J (1995) Visual search for singleton feature targets within and across feature dimensions. Percept Psychophys 57:1–17

Müller HJ, Krummenacher J, Heller D (2004) Dimension-specific inter-trial facilitation in visual search for pop-out targets: evidence for a top-down modulable visual short-term memory effect. Vis Cogn 11:577–602

Reynolds JH, Chelazzi L, Desimone R (1999) Competitive mechanisms subserve attention in Macaque areas V2 and V4. J Neurosci 19:1736–1753

Sagi D, Julesz B (1984) Detection versus discrimination of visual orientation. Perception 13:619–628

Slotnick SD, Hopfinger JB, Klein SA, Sutter E (2002) Darkness beyond the light: attentional inhibition surrounding the classic spotlight. Neuroreport 13:773–778

Slotnick SD, Schwarzbach J, Yantis S (2003) Attentional inhibition of visual processing in human striate and extrastriate cortex. Neuroimage 19:1602–1611

Theeuwes J (1991) Cross-dimensional perceptual selectivity. Percept Psychophys 50:184–193

Theeuwes J (1992) Percptual selectivity for color and form. Percept Psychophys 51:599–606

Treisman AM, Gelade G (1980) A feature-integration theory of attention. Cognit Psychol 12:97–136

Treisman AM, Sato S (1990) Conjunction search revisited. J Exp Psychol Hum Percept Perform 16:459–478

Wei P, Zhou X (2006) Processing multidimensional objects under different perceptual loads: the priority of bottom-up perceptual saliency. Brain Res 1114:113–124

Wolfe JM (1994) Guided search 20: a revised model of visual search. Psychon Bull Rev 1:202–238

Zhou X, Chu H, Li X, Zhan Y (2006) Center of mass attracts attention. Neuroreport 17:85–88