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Research Report

Processing multidimensional objects under different perceptual loads: The priority of bottom-up perceptual saliency

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ABSTRACT

The role of perceptual load in selective attention to multidimensional objects was investigated by independently manipulating the load along the task-relevant and the task-irrelevant dimensions in the central search array, which was flanked by congruent, incongruent, or neutral peripheral distractors. The relative bottom-up perceptual saliency of these dimensions in capturing attention was manipulated between experiments. When the task-relevant dimension was the color of the letter and the task-irrelevant dimension was the visual shape of the letter (Experiment 1), manipulation of the letter shape perceptual load had no impact upon the pattern of congruency effects in responding to the color, i.e., smaller congruency effects under higher color perceptual loads and larger congruency effects under lower color perceptual loads. When the task-relevant dimension was the shape of the letter and the task-irrelevant dimension was the color of the letter (Experiment 2), there were no congruency effects in responding to the letter shape under high color perceptual loads irrespective of the letter shape loads. When only the target and the flanker were colored whereas the distractors in the central array were not (Experiment 3), the task-irrelevant color information reduced or eliminated the impact of letter shape perceptual load on the congruency effects in responding to the letter shape. These findings suggested that selective attention to multidimensional objects follows the general principles suggested by the perceptual load theory, but the bottom-up perceptual saliency plays a primary role in the distribution of attentional resources over objects and dimensions.

1. Introduction

The ability to exclude distracting information and focus on a given task is vital for any coherent cognitive function. A large number of studies have been conducted to investigate how and when attention selects relevant information for further processing and prevents interference from the irrelevant information (e.g., Lavie, 2005; Pashler, 1988; Yantis and Jonides, 1990). In recent years, the classic debate between *the early selection theory* and *the late selection theory* is compromised by a hybrid model (Lavie, 1995, 2005; Lavie and Fox, 2000; Lavie and Tsal, 1994; Lavie et al., 2004), which assumes that attentional resources are limited and the perceptual load imposed by the processing of relevant information determines the extent to which irrelevant information or distractors are processed. According to this model, early selection, or successful exclusion of distractors from perception, occurs under situations of high perceptual load that exhausts

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available capacity in the processing of task-relevant information or stimuli; later selection occurs under situations of low perceptual load in which spare capacity from the relevant processing automatically "spills over" to the irrelevant distractors, resulting in the processing of distractors and its interference with the processing of the task-relevant information.

This perceptual load theory has received supports from a series of experiments, in which various manipulations of perceptual load and different measures of distractor processing are used (for a review, see Lavie, 2005). These studies typically employ a paradigm in which a target is mixed with a number of to-be-searched items in the central display, which is flanked by to-be-ignored items that could be congruent, incongruent, or neutral with the target (e.g., Lavie, 1995; Lavie and Cox, 1997; Lavie and de Fockert, 2003). The perceptual load in the central search display is manipulated by mixing the target with fewer or more distractors (e.g., Lavie and de Fockert, 2003), by mixing the target with visually uniform or non-uniform distractors (e.g., Johnson et al., 2002; Lavie and Cox, 1997), or by varying the processing requirement such that identifying the target requires either the registration of a simple feature or the integration of two features (e.g., Lavie, 1995; Chen, 2003). The flanker congruency is manipulated by varying the peripheral flanker that potentially requires either the same response as the target (in the congruent condition) or the opposite response (in the incongruent condition), or which is not in the response set (in the neutral condition). The differences between response times (RTs) to the incongruent stimuli and congruent or neutral stimuli are denoted as the flanker congruency or interference effects (Eriksen and Eriksen, 1974). It is found that the flanker interference effect is larger when processing of the central display and identifying the target are of low perceptual load, or smaller or null when processing of the central display and identifying the target are of high perceptual load (Lavie, 2005). The absence or presence of the interference effect is taken as an indicator of whether early attentional selection has taken place.

Almost all of these studies effectively treat the target and the distractors during attentional selection as single-dimension objects. Stimuli used in these studies are typically composed of letters or pictures, and the target could be different from the distractors on a number of dimensions. However, these different dimensions are neither clearly defined nor systematically manipulated in the experimental designs. It is not clear how the overall perceptual load should be defined and whether perceptual loads along different dimensions have different effects on attentional selection when the target and distractors are composed of both the task-relevant (e.g., color) and the task-irrelevant (e.g., visual shape) dimensions. Moreover, it is not clear how the perceptual load theory should be extended to the processes involved in the selection and processing of multidimensional objects. The main purpose of this study is therefore to investigate whether and how the perceptual loads of task-relevant and task-irrelevant dimensions interact to affect the distribution of attentional resources over the multidimensional targets and distractors. In particular, we aim to examine the role of the bottom-up perceptual saliency of input information in attentional selection to multidimensional objects under different perceptual loads.

We defined two dimensions of a target (and its associated flankers and distractors), such that one dimension (e.g., the visual shape of the letter) was task-relevant and another dimension (e.g., the color of the letter) was task-irrelevant. Importantly, we independently manipulated the perceptual loads of these two dimensions so that the potential effect of the perceptual load of the task-irrelevant dimension on the selecting and processing of the task-relevant information can be explicitly examined. Moreover, the relative bottom-up perceptual saliency of the two dimensions (e.g., color vs. shape) in capturing attention (Theeuwes, 1991, 1992; Chen et al., in press) was manipulated so that the potential interaction between bottom-up saliency of the input information and top-down selectivity of the task set in consuming attentional resources and the associated impact upon the processing of the flanker can be examined. We hypothesized that a task-irrelevant dimension that is strong in capturing attention could override the top-down selectivity of the task set, such that it increases the overall perceptual load in identifying the target along the task-relevant dimension and changes the distribution of attentional resources over the display and the pattern of flanker effects. Such modulatory effects of the task-irrelevant dimension could help us to understand the underlying processes of attentional selection to multidimensional objects.

It is important to note that the above reasoning implicitly assume that the task-irrelevant dimension of the stimuli in the central search display (and possibly also the flanker) must be processed and this processing consumes attentional resources. This assumption is consistent with findings concerning "object-based attention" (e.g., Duncan, 1984; Egly et al., 1994; O'Craven et al., 1999; for a review, see Scholl, 2001). Attention may select perceptual units or objects that are organized by preattentive processes, and the focusing of attention on a particular object results in the mandatory processing of all attributes or dimensions of that object (e.g., Kahneman et al., 1992; but see Allport, 1993, Maruff et al., 1999). The activation of the task-irrelevant dimension, however, may interfere with or facilitate the processing of the task-relevant dimension (e.g., Stuart et al., 2003; Eltiti et al., 2005) as many classic findings, such as the Stroop effect (Stroop, 1935, MacLeod, 1991) or the Garner effect (Garner, 1974, 1978; Garner and Felfoldy, 1970) have demonstrated. Parallel or co-activation of different dimensions has also been repeatedly observed in the study of dimensionally redundant visual search (e.g., Cohen and Magen, 1999; Krummenacher et al., 2001, 2002; Mordkoff and Yantis, 1993; Müller et al., 1995), although in such studies both dimensions are potentially task-relevant.

It is also important to note that, selective attention to multidimensional objects includes at least two components: one is to discriminate the target from its distractors and another is to differentiate the task-relevant feature from the task-irrelevant features of an object. These two components are likely to be concurrent and are not necessarily independent or interactive in nature (see, for example, Krummenacher et al., 2001, 2002 for discussions). Whether the perceptual load of one dimension of the search array has impacts upon the consumption of attentional resources (and hence the early or late attentional selection of the target) may depend not only on the task relevancy of this dimension, but also on its relative bottom-up saliency in capturing attention as compared with other dimensions. Unfortunately, the perceptual load theory in its current form does not provide us with insights about how the processing of the task-relevant and the task-irrelevant dimensions under different perceptual load conditions might work together to consume attentional resources and contribute to the attentional selection to multidimensional objects. In the General discussion section, we try to supplement the perceptual load theory with ideas borrowed from the dimension-weighting theory of visual selection (Krummenacher et al., 2001, 2002; Müller et al., 1995).

The present study consisted of three experiments, with essentially the same design. Participants were asked to search for a target color (Experiment 1) or letter (Experiments 2 and 3) in the central display while ignoring the congruent, incongruent, or neutral flanker in the periphery (see Figs. 1 and 3). The perceptual load of the task-relevant dimension (color in Experiment 1 and letter shape in Experiments 2 and 3) and the task-irrelevant dimension (letter shape in Experiment 1 and color in Experiments 2 and 3) were manipulated concurrently and orthogonally.

2. Experiment 1

The aim of Experiment 1 was to investigate whether variation of the task-irrelevant perceptual load of letter shape could consume attentional resources and affect the processing of task-relevant color information and the distribution of attention over search display and the flanker. Perceptual loads of both the task-irrelevant dimension (letter shape) and the task-relevant dimension (color of the letter) were manipulated (see Fig. 1), so that the potential interactions between them and their impact upon flanker congruency effects could be systematically examined.

2.1. *Results*

Incorrect responses were first excluded from the analyses of reaction times (RTs). RTs that were three standard deviations (STD) away from the mean in each experimental condition were considered as outliers (1.4% of the total data points) and

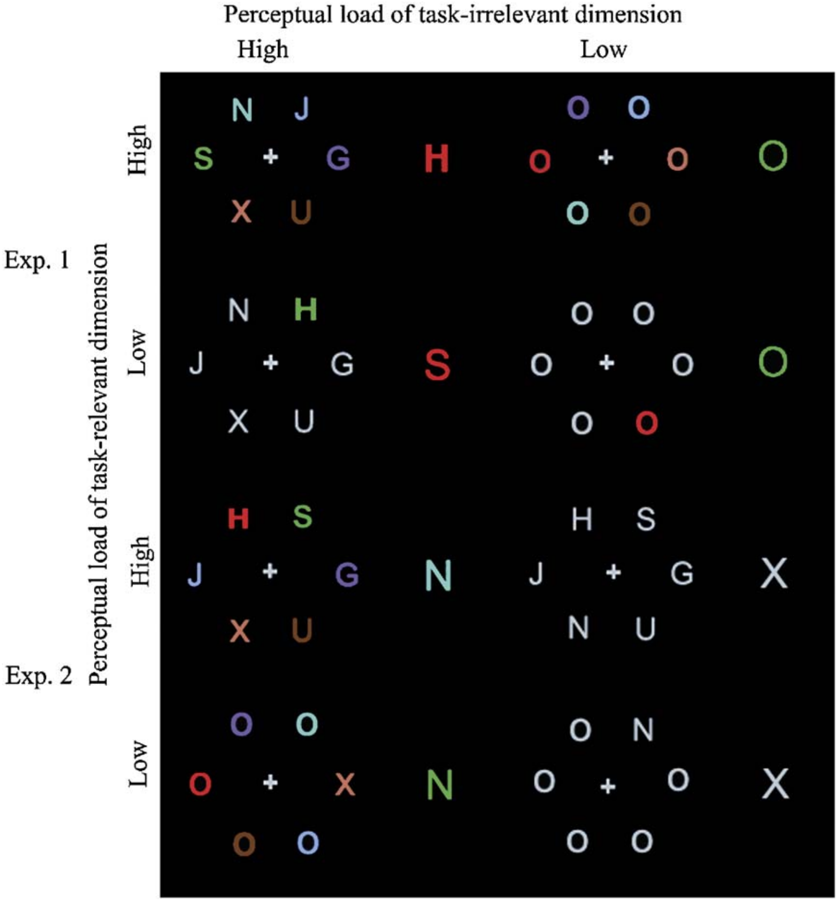

Fig. 1 – Examples of stimulus presentation according to conditions of task-relevant and task-irrelevant perceptual loads in Experiments 1 and 2. All the flanker conditions depicted in the figure are incongruent. The color and letter shape were, respectively, task-relevant and task-irrelevant dimensions in Experiment 1 and task-irrelevant and task-relevant dimensions in Experiment 2. Participants were asked to search for the target feature (red vs. green in Experiment 1; letter X vs. N in Experiment 2) in the central display and to make choice responses.

were excluded from further analysis. Mean RTs and response error percentages are reported in Table 1. Congruency effects in terms of the differences between RTs to incongruent and neutral stimuli are depicted in the top panel of Fig. 2.

An analysis of variations (ANOVA) was conducted on RTs, with the task-relevant color perceptual load (low vs. high), the task-irrelevant letter perceptual load (low vs. high), and congruency between the target color and the flanker color (congruent vs. incongruent vs. neutral) as three within-participant factors. The main effect of letter perceptual load was significant, $F(1,23) = 5.59$, $p < 0.05$, suggesting that the overall response times were slower when the letters in the central search array were varied (631 ms) than when they were the same (612 ms). This effect did not interact with any other variables ($p > 0.1$), indicating that the slowing down of RTs was to the same extent for stimuli with the high color load (21 ms) and the low color load (17 ms). The main effect of color perceptual load was highly significant, $F(1,23) = 64.00$, $p < 0.001$, indicating that participants took longer time to make color choice responses when the color target was accompanied by distractors with variable colors (663 ms) than by distractors with the same colors (580 ms). The main effect of flanker congruency was also highly significant, $F(2,46) = 56.46$, $p < 0.001$. Bonferroni-corrected pairwise comparisons showed that the mean RT in the congruent condition (606 ms) was significantly faster than RTs in the incongruent condition (634 ms, $p < 0.001$) and the neutral condition (615 ms, $p < 0.05$). The latter two also differed from each other ($p < 0.001$).

Moreover, the interaction between flanker congruency and color perceptual load was significant, $F(2,46) = 3.35$, $p < 0.05$, suggesting that the magnitudes of congruency effects, collapsed over high and low letter perceptual loads, were different for the low and high color perceptual load conditions (34 ms vs. 24 ms, against the neutral baselines). However, the interaction between letter perceptual load and congruency was not significant, $F(2,46) < 1$, suggesting that, collapsed over color perceptual load, the congruency effect did not vary over letter perceptual load conditions: against the neutral baselines, the congruency effect was 30 ms for the high letter perceptual load and 28 ms for the low letter perceptual load. Furthermore, there was no three-way interaction between congruency, color perceptual load and letter perceptual load, $F(2,46) = 1.95$, $p > 0.1$, indicating that the variation of the congruency effects over high and low color perceptual loads had the same pattern whether the distractor letters were of the same shape or different shapes. It is clear from Table 1 and Fig. 2 that the congruency effects were, irrespective of letter perceptual loads, both larger in the low color perceptual load conditions (34 ms and 33 ms) than in the high color perceptual load conditions (25 ms and 23 ms). These congruency effects were all statistically significant ($p < 0.05$) by themselves in further t tests for the simple effects.

The analysis of error rates revealed only a significant main effect of color perceptual load, $F(1,23) = 11.44$, $p < 0.005$, which indicated that participants made more response errors in the high load conditions (3.8%) than in the low load conditions (2.3%). No other effects or interactions reached significance.

2.2. *Discussion*

Findings in this experiment were consistent with the perceptual load theory. When participants responded to the task-relevant color dimension of an object, the manipulation of perceptual load along this dimension had a significant impact upon the flanker congruency effects, such that larger effects were obtained in the low load conditions than in the high load conditions. Thus, the variation of colors in the central search display consumed attentional resources, resulting in less spare attention to spill over to the peripheral flanker.

Furthermore, the variation of the perceptual load in the task-irrelevant letter shape dimension did not affect the above pattern of the modulation of congruency effects by the task-relevant color perceptual load. Parallel congruency effects were observed for stimuli with a single letter shape (i.e., “O”) and for stimuli with variable letter shapes (see the top panel of Fig. 2). One might suggest that participants could ignore the task-irrelevant dimension of objects and concentrate on the processing of the task-relevant dimension (e.g., Allport, 1993; Maruff et al., 1999). Thus, no attentional resources are distributed at all to the task-irrelevant dimension and no impact would be exerted on the pattern of flanker effects for the task-relevant dimension. However, the general slow down of responses, by 19 ms, to stimuli with variable letter shapes than to stimuli with a single letter shape suggests that participants could not ignore completely the variation in the task-irrelevant dimension. According to the logic proposed by Garner (1974, 1978, Garner and Felfoldy, 1970), if a condition with variation of the task-irrelevant dimension, as compared with a condition without this variation, showed interference in processing the task-relevant information, this must imply

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

	Load of task-irrelevant dimension	High		Low	
	Load of task-relevant dimension	High	Low	High	Low
Experiment 1	Congruent	665 (4.5)	569 (1.9)	637 (3.8)	555 (2.0)
	Incongruent	691 (4.1)	615 (3.0)	672 (4.0)	596 (2.8)
	Neutral	666 (3.3)	581 (2.0)	649 (3.2)	563 (1.9)
Experiment 2	Congruent	814 (12.4)	628 (2.9)	766 (11.3)	617 (2.5)
	Incongruent	810 (14.8)	638 (5.1)	785 (11.2)	659 (4.5)
	Neutral	809 (13.1)	637 (3.5)	773 (11.3)	627 (3.7)

Note. The task-irrelevant dimension is the letter shape and the task-relevant dimension is the color in Experiment 1, whereas the task relevancy was reversed in Experiment 2. The congruent, incongruent, and neutral indicate the relationship between the target in central display and the peripheral flanker.

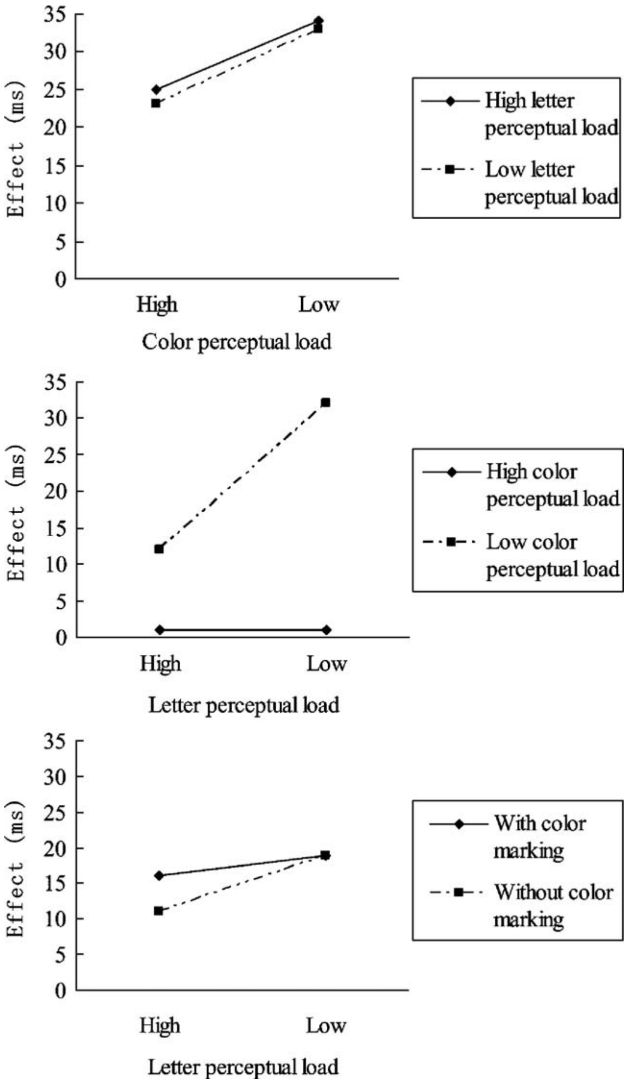

Fig. 2 – Flanker congruency effects, in terms of the differences between RTs to incongruent stimuli and neutral stimuli, as functions of perceptual loads of task-relevant and task-irrelevant dimensions in Experiments 1, 2, and 3. Top panel, effects in Experiment 1 (with the color as the task-relevant dimension); middle panel, effects in Experiment 2 (with the letter shape as the task-relevant dimension); bottom panel, effects in Experiment 3 (with the letter shape as the task-relevant dimension).

that the task-relevant and the task-irrelevant dimensions are “integral” and the variation in the task-irrelevant dimension inevitably attracts attention and consumes resources. Thus, the visual shape and color are the two integrated dimensions of the letters and they cannot be processed independently. In other words, the two dimensions of the target and distractors are co-activated (Krummenacher et al., 2001, 2002).

Why then the consumption of attentional resources by the processing of letter shapes in the central display did not affect the spillover of spare attentional resources to the flanker and the pattern of flanker interference effects for the color? One possible reason is that compared with color, visual form is normally less prominent in capturing attention (Theeuwes, 1991, 1992; Chen et al., in press). Although the variation of visual shape in the central display slowed down the search and identification of the target color in this experiment, it did not consume too much attentional resources and thus had no major impact on the automatic distribution of spare resources to the peripheral flanker. Moreover, because the task-relevant dimension was color and color in general has the priority in capturing attention over shape, the colored flanker itself may have some advantages in consuming attentional resources over visual shapes in the central display. In these ways the pattern of congruency effects for the high and low color perceptual loads was not affected by the manipulation of the letter perceptual load.

However, if the assignment of the asymmetric color and letter shape to task-relevant and task-irrelevant dimensions is reversed such that the more salient dimension, color, is task-irrelevant, we predict that processing of this dimension would attract more attentional resources and have stronger influences on the distribution of attention over the central display and the flanker. It is then possible that no spare attentional resources would be left for the peripheral flanker when the perceptual load of the task-irrelevant dimension (color) is high. This prediction is tested in the next experiment.

3. Experiment 2

Experiment 2 was basically a mirrored version of Experiment 1 (see Fig. 1), with the assignment of the task-relevant and task-irrelevant dimensions reversed over color and letter shape.

3.1. *Results*

Trials with incorrect responses were excluded from data analysis. Mean RTs and error rates were then calculated for each participant after deleting outliers three STD away (1.4%) from the mean in each experimental condition. Mean RTs and error percentages are reported in Table 1. Congruency effects in terms of the differences between RTs to incongruent and neutral stimuli are depicted in the middle panel of Fig. 2.

An ANOVA was conducted on RTs, with the task-relevant letter perceptual load (low vs. high), the task-irrelevant color perceptual load (low vs. high) and the flanker congruency (congruent vs. incongruent vs. neutral) as three within-participant factors. The main effect of color perceptual load was significant, $F(1,24)=7.35$, $p<0.05$, indicating that RTs were faster when stimuli had no color (704 ms) than when stimuli had colors (723 ms). This effect interacted with the letter perceptual load, $F(1,24)=7.43$, $p<0.05$, suggesting that the differences between RTs to no-color stimuli and colored stimuli were larger when the letter perceptual load was high (37 ms) than when the letter perceptual load was low (0 ms). The main effect of letter perceptual load was highly significant, $F(1,24)=127.91$, $p<0.001$, with responses faster to low load stimuli (635 ms) than to high load stimuli (793 ms). The main effect of congruency was also significant, $F(2,48)=8.42$, $p<0.005$. Bonferroni-corrected pairwise comparisons showed that the overall RTs in the incongruent conditions (723 ms) were significantly slower than RTs in the congruent conditions (706 ms, $p<0.005$) and the neutral conditions (711 ms, $p<0.05$), whereas the latter two did not differ from each other ($p>0.1$).

The interaction between congruency and color perceptual load was significant, $F(2,48)=3.74$, $p<0.05$. The interaction between congruency and letter perceptual load was marginally significant, $F(2,48)=2.51$, $0.05<p<0.1$. However, the three-way interaction was not significant, $F(2,48)<1$. Separate ANOVAs were then conducted for RTs in the low and high color perceptual load conditions, with letter perceptual load and congruency as two within-participant factors. For the high color perceptual load conditions, although there was a main effect of letter perceptual load, $F(1,24)=121.65$, $p<0.001$, with responses faster to low load stimuli (635 ms) than to high load stimuli (811 ms), there was no effect of congruency, $F(2,48)<1$, nor the interaction between congruency and letter perceptual load, $F(2,48)<1$.

For the low color perceptual load conditions, the main effect of letter perceptual load was significant, $F(1,24)=87.29$, $p<0.001$, with responses faster to low load stimuli (634 ms) than to high load stimuli (774 ms). More importantly, the main effect of congruency was significant, $F(2,48)=27.93$, $p<0.001$, so was the interaction between congruency and letter perceptual load, $F(2,48)=3.26$, $p<0.05$. Further tests showed that there was a significant congruency effect in the low letter perceptual load condition, $F(2,48)=75.30$, $p<0.001$, with RTs in the incongruent condition (659 ms) significantly slower ($p<0.001$) than RTs in the congruent condition (617 ms) and neutral condition (627 ms). The difference between the congruent and neutral conditions also reached significance ($p<0.05$). The congruency effect in the high letter perceptual load condition was only marginally significant, $F(2,48)=2.54$, $0.05<p<0.1$.

Analyses of error rates revealed a significant main effect of letter perceptual load, $F(1,24)=67.05$, $p<0.001$, with more errors committed to high load stimuli (12.4%) than to low load stimuli (3.7%). The main effect of congruency was also significant, $F(2,48)=4.56$, $p<0.05$, with more errors on incongruent stimuli (8.9%) than on congruent stimuli (7.3%) or the neutral stimuli (7.9%). The main effect of color perceptual load was marginally significant, $F(1,24)=3.75$, $0.05<p<0.1$. No other effects or interactions reached significance.

3.2. *Discussion*

To summarize, when the perceptual load in the task-irrelevant dimension was low (i.e., all the letters in a display being dimly white), a typical pattern of perceptual load effects was observed for the task-relevant dimension (i.e., the letter shape), with a large flanker congruency effect in the low letter perceptual load condition and a reduced congruency effect in the high letter perceptual load condition. When the perceptual load in the task-irrelevant dimension was high (i.e., letters in the display being of different colors), no congruency effects were observed for the task-relevant dimension, in either the low or high letter perceptual load condition. Moreover, when the task-relevant letter perceptual load was low, the overall mean RTs were not affected by whether the task-irrelevant dimension (color) was varied or not; when the letter perceptual load was high, responses were slowed down by the variation of color dimension. These findings suggest that when the task-irrelevant dimension (e.g., color) of an object is strong in capturing attention, processing of the weaker, task-relevant dimension (e.g., letter shape) is slowed down, especially when the current task is hard to complete (e.g., when the target has to be searched from variable distractors). More importantly, when processing of the salient task-irrelevant dimension depletes attention, no spare resources will be distributed to the task-relevant dimension of an object in the periphery, irrespective of the current task is of low or high perceptual load.

The finding of no congruency effect for the low letter perceptual load stimuli with variable colors was perhaps surprising, especially given the fact that the overall RTs in this condition were not different from RTs in the low letter load, low color load condition, which showed a large congruency effect (see the middle panel of Fig. 2). It seems that distribution of attentional resources over the display has a strong impact upon the processing of peripheral flanker, but it has only a weak or null effect on the overall efficiency of search and identification of the target. The absence of congruency effects in the high color perceptual load conditions, irrespective of the perceptual load of task-relevant letter perceptual load, demonstrated that the top-down task set cannot prevent the grab of attentional resources by the automatic processing of a salient dimension of objects, even though this dimension is completely task-irrelevant. We defer the discussion of how these processes might take place to the General discussion section.

The finding of the slow down of responses to the target with distractors of variable letter shapes, which were also varied along the task-irrelevant color dimension, confirmed the argument in Experiment 1 that visual shape and color are the two integrated dimensions of the letter object. The finding of no difference in the overall RTs to stimuli with or without colors in the two low letter perceptual load conditions did not contradict this argument. It is clear from Table 1 that in both congruent and neutral conditions, RTs to stimuli with colors were indeed about 10 ms slower than RTs to stimuli without color (i.e., 628 ms vs. 617 ms; 637 ms vs. 627 ms). It was only that RTs to the incongruent stimuli with color was 21 ms faster than RTs to the incongruent stimuli without color (i.e., 638 ms vs. 659 ms). This faster responses, however, was due to the fact that there were no spare attentional resources to spill over to the flanker and the flanker did not cause interference with the processing of the target. In other words, the variation of the task-irrelevant dimension (color) in the central search display, although consuming more attentional resources, could actually prevent the target from suffering from interference from the flanker, thus making the response to the target quicker.

4. Experiment 3

Experiment 2 found that the variation of the task-irrelevant color over the displayed objects could dramatically consume attentional resources and cause the reduction of flanker congruency effects for the task-relevant letter shape. This effect, however, depends crucially on the bottom-up saliency

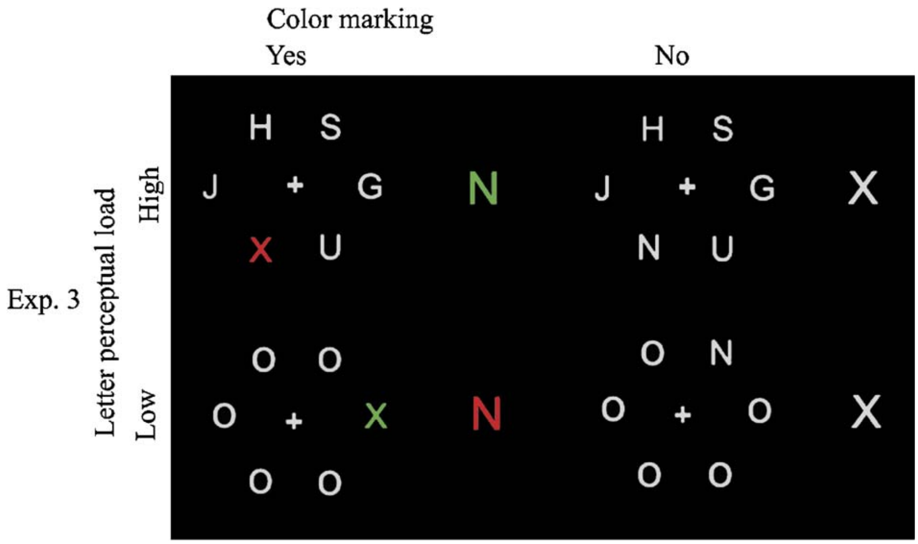

Fig. 3 – Examples of stimulus presentation according to conditions of task-relevant perceptual load and color marking in Experiment 3. All the flanker conditions depicted in the figure are incongruent. Participants were asked to search for the target letter (X vs. N) in the central display and to make choice responses.

of color in capturing attention as similar manipulations over the less salient letter shape did not lead to such interactions in Experiment 1. Experiment 3 was to demonstrate that the bottom-up saliency of the task-irrelevant color dimension can also function in an opposite way: by overriding the influence of perceptual load in the task-relevant dimension and leading to the same amount of congruency effects in both conditions of high and low letter perceptual load.

As in Experiment 2, participants were asked to search for a target letter in the central display while ignoring the flanker at the periphery. Unlike Experiment 2, however, instead of having all the letters colored in a display in the high color perceptual load conditions, this experiment had only the target and the flanker colored or marked (Fig. 3), whereas the target letter could be accompanied by five letter Os (in the low letter perceptual condition) or by G, H, J, S, and U (in the high letter load condition). We expect that the color information for the target (and for the flanker) could serve as a guide to help participants to locate and identify the target (and the flanker). The impact of high perceptual load in the task-relevant letter dimension upon the congruency effect could then be overridden.

Table 2 – Mean reaction times (ms) and error percentages (in parentheses) in Experiment 3

Color marking	Yes		No	
Load of task-relevant dimension	High	Low	High	Low
Congruent	599 (1.9)	584 (1.9)	748 (8.5)	596 (1.7)
Incongruent	622 (3.1)	608 (2.8)	752 (8.1)	618 (4.1)
Neutral	606 (2.6)	589 (2.4)	741 (6.9)	599 (1.4)

Note. The task-relevant dimension is the letter shape. The congruent, incongruent, and neutral indicate the relationship between the target in the central display and the peripheral flanker.

4.1. *Results*

Trials with incorrect responses were excluded from data analysis. Mean RTs and error rates were then calculated for each participant after outliers three STD away from the mean (1.3% of the total data points) in each experimental condition were removed. They are reported in Table 2. Congruency effects in terms of the differences between RTs to incongruent and neutral stimuli are depicted in the bottom panel of Fig. 2.

An ANOVA was conducted on RTs, with letter perceptual load, color marking, and congruency as three within-participant factors. The main effect of color marking was significant, $F(1,23)=203.57$, $p<0.001$, with RTs faster to stimuli with color marking (601 ms) than to stimuli without color marking (675 ms). The main effect of letter perceptual load was significant, $F(1,23)=265.15$, $p<0.001$, indicating that the responses were faster to stimuli with low load (599 ms) than to stimuli with high load (678 ms). The interaction between color marking and letter perceptual load was also significant, $F(1,23)=122.80$, $p<0.001$, indicating that the benefit of having the target and flanker color-marked was manifested mainly in stimuli with high letter perceptual load (609 ms vs. 747 ms) rather than on stimuli with low letter perceptual load (594 ms vs. 604 ms).

The main effect of congruency was significant, $F(2,46)=32.98$, $p<0.001$, so was the interaction between congruency and color marking, $F(2,46)=3.32$, $p<0.05$. The interaction between congruency and letter perceptual load was marginally significant, $F(2,46)=2.57$, $0.05<p<0.1$. Separate ANOVAs were then conducted for stimuli with color marking and stimuli without color marking, with letter perceptual load and congruency as two within-participant factors. For stimuli with color marking, there was a main effect of letter perceptual load, $F(1,23)=7.55$, $p<0.05$, with RTs faster in the low load conditions (594 ms) than in the high load conditions (609 ms). There was also a main effect of congruency, $F(2,46)=40.10$,

$p < 0.001$, but no interaction between congruency and letter perceptual load, $F(2,46) < 1$. This suggested that there were equal and significant congruency effects (23 ms for incongruent vs. congruent and 18 ms for incongruent vs. neutral) in both high and low letter perceptual load conditions when the target and the flanker were color marked. For stimuli without color marking, the main effects of both letter perceptual load, $F(1,23) = 241.76$, $p < 0.001$ and congruency, $F(2,46) = 10.20$, $p < 0.001$, were significant. However, the interaction between them was also marginally significant, $F(2,46) = 2.83$, $0.05 < p < 0.1$, indicating that the congruency effect in the low letter load condition was larger than the effect in the high load condition. Further Bonferroni-corrected tests showed that the differences between RTs to the congruent, incongruent, and neutral stimuli in the high load condition did not reach significance, $F(2,46) = 1.56$, $p > 0.1$, but the differences in the low load condition did, $F(2,46) = 21.40$, $p < 0.001$. RTs to the incongruent stimuli (618 ms) were faster ($p < 0.001$) than RTs to the congruent stimuli (596 ms) and neutral stimuli (599 ms).

Analyses of error rates found a significant main effect of color marking, $F(1,23) = 63.10$, $p < 0.001$, with more errors committed to stimuli without color marking (5.1%) than to stimuli with color marking (2.5%). The main effect of letter perceptual load was also significant, $F(1,23) = 46.39$, $p < 0.001$, indicating that there were more response errors in the high load conditions (5.2%) than in the low load conditions (2.4%). The interaction between them was significant, $F(1,23) = 51.15$, $p < 0.001$, suggesting that the above differences were mainly because the error rate in the high perceptual load condition without color marking (7.8%) was much higher than error rates in the other three conditions (2.5%, 2.4% and 2.4%, respectively). The main effect of congruency was significant, $F(2,46) = 4.74$, $p < 0.05$, suggesting that more errors were made to incongruent stimuli (4.5%) than to congruent stimuli (3.5%) or neutral stimuli (3.4%). The interaction between congruency and color marking was marginally significant, $F(2,46) = 3.04$, $0.05 < p < 0.1$.

4.2. *Discussion*

The pattern of congruency effects for stimuli without color marking was consistent with the pattern of effects for stimuli with low color perceptual load in Experiment 2, with a larger effect in the low letter perceptual load condition and a reduced effect in the high letter perceptual load condition. When the target in the central search display and the peripheral flanker was color marked, however, equivalent congruency effects were observed for the low and high letter perceptual load conditions. This pattern was different from the finding for the high color perceptual load conditions in which all the items in the central search display were colored (i.e., in Experiment 2).

This change of coloring for the central display may have had a fundamental impact upon participants' strategies in searching for the target. In this experiment, because all distractors in the search display were non-colored and only the target was colored, participants may use a singleton search mode to locate the target (e.g., Bacon and Egeth, 1994; Lamy et al., 2004). In other words, processing of the task-irrelevant color dimension did not hinder the searching for the target, as in Experiment 2, but helped to locate the target, irrespective of the accompanied distractors being of the same or different letter shapes. Indeed, the finding of the faster RTs to stimuli with color marking than to stimuli without color marking supports this argument.

A consequence of this color-marking was that, compared with conditions without color marking, there could be more spare attentional resources left when the colored target was being located and identified. According to the perceptual load theory, these spare attentional resources would automatically spill over to the flanker, leading to interference with the response to the target. The fact that the flanker was also colored in the color marking conditions makes the flanker to attract attention more easily. Similar results were also obtained by Eltiti et al. (2005) who found that when the target was more salient (e.g., the target was larger than other items in the central display) or when the target and the flanker both appeared as offsets, the peripheral flanker was processed irrespective of the perceptual load of the central display.

Even though information in the task-irrelevant color dimension helped to guide the localization and identification of the target, variation along the task-relevant letter shape dimension still played a general role in modulating responses to the target in the color marking conditions. The overall RTs in the high letter perceptual load conditions were still significantly slower (15 ms) than RTs in the low letter load conditions. However, this difference did not significantly affect the congruency effects in the high and low perceptual load conditions. The colored flanker has the priority to use the spare attentional resources left by the easy task of finding the target letter.

5. General discussion

Main findings from the three experiments can be summarized as following. When the task-irrelevant dimension was the visual shape of letters and the task-relevant dimension was the color of letters (Experiment 1), manipulation of the letter shape perceptual load had no effect on the distribution of attentional resources to color, with stimuli of low or high letter perceptual loads showing the same pattern of flanker effects: larger congruency effects in the low color perceptual load conditions and smaller congruency effects in the high color perceptual load conditions (Fig. 2, top panel). When the task-irrelevant dimension was the color of letters and the task-relevant dimension was the visual shape of letters (Experiment 2), however, manipulation of the perceptual load of color had a significant impact on the pattern of flanker effects for the letter shape, with congruency effects in both high and low letter perceptual load conditions being completely wiped out by the high color perceptual load (Fig. 2, middle panel). When the target and the flanker were singled out by the task-irrelevant colors and participants responded to the visual shape of the target letter (Experiment 3), however, significant and equivalent congruency effects were observed in high and low letter perceptual load conditions (Fig. 2, bottom panel). Normal patterns of congruency effects for the letter shape were observed in Experiments 2 and 3 when the task-irrelevant color dimension was of low perceptual load (i.e., when all the letters in a display were dimly white).

These findings demonstrate that distribution of attentional resources over multi-dimensional objects generally follows the principles suggested by the perceptual load theory of selective attention (Lavie, 1995, 2005; Lavie and Cox, 1997; Lavie and Tsal, 1994). When the perceptual load of identifying the target is high, whether because attentional resources have to be spent on discriminating the target from distractors varying along the task-relevant dimension and/or on processing the task-irrelevant dimension with a higher bottom-up perceptual saliency, less attentional resources are left to spill over to the flanker, resulting in smaller or null flanker congruency effects. More importantly, the present findings extend the perceptual load theory by showing that the consumption of attentional resources and the spillover of spare attentional resources to the periphery is constrained not only by the perceptual load of the task-relevant dimension, but also by the perceptual load of the task-irrelevant dimension, especially when the task-irrelevant dimension is of higher perceptual saliency in capturing attention than the task-relevant dimension. The bottom-up perceptual saliency could play a primary role in the distribution of attentional resources over different objects and over different dimensions of the objects, overriding the top-down task set.

The perceptual load theory in the present form does not provide a specific framework about how the attentional resources are distributed and consumed in processing multi-dimensional objects in the search display. To explore the possible processes involved in processing multidimensional objects under different perceptual loads, we borrow ideas from the dimension-weighting theory of visual selection (Krummenacher et al., 2001, 2002; Müller et al., 1995), which proposes that target detection in visual search involves an attentional mechanism that modifies the processing system by allocating selection weight to the various dimensions that potentially define the target. We hope that our discussion here will lead to further studies on how the processing of the task-relevant and the task-irrelevant dimensions might interact and how this interaction might be modulated by perceptual load and by the relative perceptual saliency between the dimensions.

It is commonly assumed that at the lowest level of visual processing, there are dimension-specific input modules, such as color, orientation, brightness, motion, etc. According to the Feature Integration theory (Treisman and Gelade, 1980; Treisman and Sato, 1990) and the Guided Search model (Cave and Wolfe, 1990; Wolfe, 1994), visual features are analyzed preattentively and registered in parallel to form spatiotopically organized feature maps. In these maps, saliency signals for all stimulus locations are computed to indicate the feature contrast of one particular item to the various other items represented within the same module. The more dissimilar an item is, as compared with the others in the vicinity, the greater its saliency. Maps of saliency signals are summed onto a master map of activations, and the activity on the master map guides focal attention, with the most active location being sampled with priority. In other words, attention operates on a master map of integrated (summed) saliency signals derived separately in dimension-specific input modules. However, dimension-specific saliency information is likely to be attentionally weighted prior to signal integration by the master map units, as studies on visual search with redundant dimensions have demonstrated (Krummenacher et al., 2001, 2002; Müller et al., 1995). The greater the weight assigned to the target dimension, the greater the rate for a feature difference within this dimension accumulates at the master map level. The crucial assumption here is that there is a limit to the total attentional weight available to be allocated at any one time to the various dimensions of the target object. Potential target-defining dimensions may be assigned weight in accordance with their instructed importance and/or their variability across trials.

Because the dimension-weighting theory was proposed on the evidence from redundant singleton search in which different dimensions are all potentially task-relevant (Krummenacher et al., 2001, 2002; Müller et al., 1995), this theory does not explicitly define how the signals from a task-irrelevant dimension should be weighted in their transmission to the master map. It has been argued that different dimensions are not assigned with equal weights (Krummenacher et al., 2001, 2002; Müller et al., 1995). Other things being equal, some dimensions (e.g., color) are more perceptually salient and hence are assigned with stronger weights than other dimensions (e.g., visual shape; Theeuwes, 1991, 1992). Moreover, it can be assumed that although the task instruction or task set may alter the default weight assignment by putting more weights to signals from the task-relevant dimension, this top-down modulation cannot, at least in certain circumstances, prevent the signals for the highly salient task-irrelevant dimensions (e.g., color) from getting stronger weights in their transmission to the master map and having higher activations there than the signals for the less salient task-relevant dimension. This assumption is consistent with many studies showing that a task-irrelevant singleton distractor can capture attention and cause interference (e.g., Theeuwes, 1991, 1992).

In the present study, the saliency signal for the target in the task-relevant dimension is relatively higher when all the distractors in that dimension are uniform (i.e., in the low load conditions) and it is lower when the distractors are variable (i.e., in the high load conditions). This within-dimension perceptual saliency directly affects how the attentional resources are to be spent in searching for the target in the master map, with fewer resources consumed when the target signal is high and more resources consumed when the signal is low. Attentional resources, however, are spent not only in processing the task-relevant dimension, but also in processing the task-irrelevant dimension, especially when the task-relevant and the task-irrelevant dimensions are bound together on the same objects and when the task-irrelevant dimensions are automatically assigned higher attentional weights. Consequently, when the task-relevant dimension is strongly weighted compared with the task-irrelevant dimension (e.g., color vs. letter shape in Experiment 1), saliency signals from this stronger dimension have higher activations in the master map and the overall perceptual load in search for the target in the master map is hence determined mostly by this dimension. In contrast, when the task-relevant dimension is weakly weighted compared with the task-irrelevant dimension (letter shape vs. color in Experiment 2), although the task set could revise the default weight for the signals for the letter shape dimension to be higher, this top-down modulation is not sufficient to override the default, stronger weight assignment to the task-irrelevant color dimension. The underlying message here is that it is the bottom-up perceptual saliency rather than the task set that plays an upper hand in determining the activations in the master map.

The priority of bottom-up saliency in search for the master map for the target can also be found when the salient task-irrelevant dimension is useful to locate the target and to save attentional resources. When searching for a target along the task-relevant dimension is made easy by the task-irrelevant singleton singling out this target, not only responses to the target under the high perceptual load along the task-relevant dimension are facilitated, but also the congruency effect is elevated. That is, although the overall response to the target is made faster, this facilitation leaves more spare attentional resources and processing of this target actually suffers more from interference from processing of the flanker. This phenomenon is consistent with the previous finding suggesting that “efficient visual search leads to inefficient distractor rejection” (Lavie and Cox, 1997).

To conclude, by defining and manipulating the perceptual loads along the task-relevant and the task-irrelevant dimensions of multidimensional objects in the search array and by manipulating the relative bottom-up saliency of these dimensions in capturing attention, this study demonstrated that selective attention to multidimensional objects is subject to constraints of perceptual loads along both task-relevant and task-irrelevant dimensions. However, the relative bottom-up saliency of dimensions, rather than the task relevancy of these dimensions, plays a dominant role in determining the distribution of attentional resources over different objects and over different dimensions of the objects. The perceptual load theory needs to be extended to provide a detailed account for how the processing of the task-relevant and the task-irrelevant dimensions might interact under different perceptual loads and how the relative perceptual saliency between the dimensions could play a role in this interaction.

6. Experimental procedures

6.1. *Experiment 1*

6.1.1. *Participants*

Twenty-four undergraduate students from Peking University took part in the experiment. They were right handed and had normal or corrected-to-normal vision without color blindness or weakness. They gave their informed consent to participate in the experiment and were paid for their participation.

6.1.2. *Stimuli and design*

This experiment consisted of three factors. The first factor was the perceptual load along the task-irrelevant dimension, which was the letter shape. Letters in a display could be either of the same shape (the letter O, for the low load conditions) or of different shapes (letters of X, N, G, H, J, S, and U, for the high load conditions). The second factor was the perceptual load along the task-relevant dimension, which was the color. Letters in a display, except the target letter and the flanker, could be either of the same color (i.e., dimly white) or of different colors (orange, purple, brown, blue, and indigo). The target was either red or green, and the flanker was red, green, or gray. The third factor was the congruency between colors of the target and the flanker, which was congruent (e.g., both the target and the flanker being red), incongruent (e.g., the target being red and the flanker being green), or neutral (e.g., the target being red and the flanker being gray). The three factors crossed to form a 2×2×3 within-participant design.

Each experimental condition had 60 trials, with each trial consisted of a central search display and a flanker at the periphery. The central display had six colored letters, which formed an imaginary circle around a fixation cross. The combination of a color with a letter was randomly assigned in each display. No letter or color or their combination was used twice in each display.

6.1.3. *Procedure*

The presenting of stimuli and recording of response times and error rates were controlled by Presentation software (http://nbs.neuro-bs.com/). At the start of each trial a white fixation cross measuring 0.20° of visual angle appeared in the center of the black screen for 1000 ms, together with six dots surrounding the fixation. These dots formed an imaginary circle and indicated the locations of colors to be searched. Then six colored letters appeared on these locations, together with a colored flanker letter at either left or right side of the letter circle. The center-to-center distance between central fixation and each letter around the fixation was 1.3° of visual angle, and the distance between central fixation and the peripheral flanker was 3.2°. Each letter in the central display extended 0.9° of visual angle vertically and 0.7° horizontally, with the distance between adjacent letters being equal. The flanker letter was also extended 0.9°×0.7° of visual angle. The viewing distance was held at 66 cm with a chin rest.

The search display and the peripheral flanker appeared for 200 ms. Participants were instructed to respond as quickly and as accurately as possible to the target color in the central search display by pressing the left button of the computer mouse for red and the right button for green. A blank screen was presented for 1800 ms after the search display.

The task-irrelevant letter perceptual load and the task-relevant color perceptual load were crossed to form four task blocks. In each block, target color (red vs. green), target position (the six positions in the central display), flanker color (red vs. green vs. gray), and flanker position (left vs. right) were randomly assigned and occurred equally often over 180 trials. The order of the four test blocks was counter-balanced over participants using a Latin-square design. Participants received 20 practice trials for each type of task block before the experiment. There was a 2-min break between blocks.

6.2. *Experiment 2*

6.2.1. *Participants*

Twenty-five undergraduate students from Peking University, not tested for Experiment 1, participated in the experiment. They all were right handed and had normal or corrected-to-normal vision without color blindness or weakness. They were paid for their participation.

6.2.2. *Stimuli and procedures*

Participants were asked to search for a target letter (X or N) among distractor letters in the central display (see Fig. 1), with the task-relevant letter perceptual load being either low or high. In the low letter perceptual load conditions, the target letter was accompanied by five distractor letters, all of them being the letter O. In the high letter perceptual load conditions, the target was accompanied by distractor letters G, H, J, S, and U. The task-irrelevant dimension, color, was also manipulated, such that in the low color perceptual load conditions all the letters in a display were dimly white whereas in the high color load conditions all the letters (including the peripheral flanker) were with colors (orange, purple, brown, blue, indigo, red, and green). The third factor, flanker congruency, had three levels, depending on whether the peripheral flanker letter was the same as the target letter in the central display, or the other target letter, or a letter not in the response set (letter T). These three factors were crossed and formed a 2×2×3 within-participant factorial design. In the high color perceptual load conditions, the seven colors were randomly distributed over the seven letters in a display (6 in the central and 1 in the periphery), with no colors used twice.

The size of letters in the display was the same as in Experiment 1. Participants were asked to respond to the target letter identity in the central display as quickly and as accurately as possible by pressing the left button of the computer mouse for X and the right button for N. The spatial and timing parameters for each display, the presentation of stimuli over blocks were the same as in Experiment 1. Each participant was tested for four blocks of 180 trials, with 60 trials for each experimental condition.

6.3. *Experiment 3*

6.3.1. *Participants*

Twenty-four undergraduate students from Peking University participated in this experiment. They all are right handed and have normal or corrected-to-normal vision without color blindness or weakness. They were not tested for Experiments 1 and 2 and were paid for participating in this experiment.

6.3.2. *Stimuli and procedures*

Stimuli and experimental procedures were essentially the same as in Experiment 2 except that only the target and the flanker were colored in the color marking conditions. The target and the flanker were either red or green, but their colors were never the same in a trial. The low color perceptual load conditions in Experiment 2 were kept but were renamed as no color-marking conditions (see Fig. 3).

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