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Effects of task-irrelevant grouping on visual selection in partial report

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Abstract Perceptual grouping modulates performance in attention tasks such as partial report and change detection. Specifically, grouping of search items according to a task-relevant feature improves the efficiency of visual selection. However, the role of task-irrelevant feature grouping is not clearly understood. In the present study, we investigated whether grouping of targets by a task-irrelevant feature influences performance in a partial-report task. In this task, participants must report as many target letters as possible from a briefly presented circular display. The crucial manipulation concerned the color of the elements in these trials. In the sorted-color condition, the color of the display elements was arranged according to the selection criterion, and in the unsorted-color condition, colors were randomly assigned. The distractor cost was inferred by subtracting performance in partial-report trials from performance in a control condition that had no distractors in the display. Across five experiments, we manipulated trial order, selection criterion, and exposure duration, and found that attentional selectivity was improved in sorted-color trials when the exposure duration was 200 ms and the selection criterion was luminance. This effect was accompanied by impaired selectivity in unsorted-color trials. Overall, the results suggest that the benefit of task-irrelevant color grouping of targets is contingent on the processing locus of the selection criterion.

Keywords Partial report · Perceptual grouping · Selective attention

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Perceptual organization in the form of perceptual grouping and figure–ground segregation is fundamental for human vision. Gestalt psychologists of the early 20th century were first to identify principles such as similarity, proximity and common movement that govern the joining and segregation of elementary parts into objects (see Wagemans et al., 2012, for a review). Such organization is a necessary prerequisite for attention—attention is attention *to* something—hence it must reside in a preattentive processing domain. Early studies of perceptual grouping confirmed this deduction by showing that grouping of nontargets by proximity (Bacon & Egeth, 1991; Treisman, 1982) or color (Bundesen & Pedersen, 1983) improves spatial attention in visual search. Furthermore, more recent evidence suggests that perceptual grouping can occur at an early as well as a late level in the visual system (Schulz & Sanocki, 2003). Schulz and Sanocki presented participants with colored disks covered by a layer of transparent color at various exposures. At short exposure durations these disks were mostly grouped with adjacent disks sharing the color that was produced by the transparency, but at longer exposures participants mostly grouped according to the "original" color. The results thus demonstrated that color grouping can occur before and after color constancy is established (although see Kraft & Brainard, 1999). Also in support of this finding, a review of perceptual grouping studies by Palmer, Brooks, and Nelson (2003) showed that grouping takes place at multiple stages in visual processing.

Automatic perceptual organization has been shown to influence attention in various visual tasks. A study by Jiang, Chun, and Olson (2004) provided evidence on the effect of perceptual grouping on selective attention in a change detection task. In their experiments, observers first viewed a memory display containing eight randomly placed black dots, each with an interposed white line segment. The line segments crossed the center of the dots and were randomly oriented in a 45° or 90° angle. Following a 1-s interstimulus interval a probe display was presented. In the probe display a single dot would be displaced in 50% of the trials, and the observers were asked to report whether such a location change was present. Observers were explicitly told to ignore the line segments while doing so. On half of the trials, the line segments changed their orientation by 45°–90° from memory display to probe display. The results showed that participants were less sensitive to dot location changes when trials included an orientation change to interposing line segments. This indicated that information from a completely task-irrelevant feature dimension (i.e., orientation) was not ignored. Jiang et al. speculated that only irrelevant features that are connected to the task-relevant feature affect performance in change detection. In other words, whether perceptual organization of features in an additional feature dimension modulates performance in a given task seems to depend on the relationship between the additional feature and the task set.

Similar discussions of the possibly detrimental role of task-irrelevant stimulus attributes have taken place in the attentional capture literature. In a paradigm now referred to as the additional singleton paradigm, Theeuwes (1991, 1992) demonstrated that a highly salient, albeit completely task-irrelevant object can capture attention and disrupt performance. Theeuwes posited that slowed reaction times in this paradigm are the consequence of a purely stimulus-driven response. However, this view was later contested by a group of researchers who emphasized the role of top-down mechanisms in producing the effect (Bacon & Egeth, 1994; Folk & Remington, 1998, 1999; Folk, Remington, & Johnson, 1992; Folk, Remington, & Wright, 1994). Bacon and Egeth hypothesized that attentional control settings must match the distractor singleton for it to cause interference. Several studies have supported the notion that singleton detection mode is necessary for attentional capture of an irrelevant singleton (Lamy & Egeth, 2003; Lamy, Tsal, & Egeth, 2003; Leber & Egeth, 2006).

An alternative paradigm for studying visual selection is the partial-report paradigm. *Partial report* entails brief exposure of a stimulus set consisting of targets and distractors, after which the observer must report as many targets as possible. It differs from visual search and additional singleton paradigms in that the dependent variable is not reaction time, but accuracy, in terms of the proportion of correctly reported targets. Arguably, by being decoupled from response-related processes, accuracy more specifically reflects the efficiency of perceptual processes. Furthermore, the inclusion of multiple target elements in partial report provides a way to study the significance of target–target similarity. It is well-known that search difficulty increases with increased target–distractor similarity and decreased similarity between distractors (Duncan & Humphreys, 1989, 1992). The relationship between target grouping and attentional selection is less well understood, perhaps because of the limited use of experimental search tasks with multiple targets. For example, it is unclear how the utility weighting mechanism of the extended generalized context model for visual search (Guest & Lamberts, 2011) generalizes to situations with multiple targets.

The goal of this study was to investigate the role of perceptual grouping by task-irrelevant features of targets in visual selection using the partial-report paradigm (Shibuya & Bundesen, 1988; Sperling, 1960). We performed five variations of the partial-report paradigm and tested the influence of trial order, exposure duration, and selection criterion on the attentional effect of irrelevant perceptual grouping. In the first experiment, participants were to report as many of a set of briefly presented letter targets as possible. On some trials the letters were accompanied by digit distractors, and the crucial manipulation concerned the color of elements in these trials. In the sorted-color condition, the color of the display elements was arranged according to the selection criterion, and in the unsorted-color condition the color was assigned randomly independent of class. Importantly, the specific target color was never consistent. In all experiments, the color of a targets on a given trial had a 50% likelihood of being either red or blue, which discouraged a purely feature-based approach in which the observer searched for an element of a particular color. Thus, any changes to performance in this task was related to the arrangement of color with respect to the selection criterion.

Experiment 1: Alphanumeric selection, intermixed trials

The aforementioned results from studies on attentional capture and change blindness suggest that irrelevant features interfere with visual selection. Thus, for this initial experiment we predicted that attentional selectivity would be more efficient in sorted-color trials than in unsorted-color trials.

Method

Participants Fifteen participants (12 female, three male) with normal or corrected-to-normal vision were recruited from the subject pool of the Center for Visual Cognition at the University of Copenhagen. Some participants were given course credit, while others received a monetary reward for participation. Their ages ranged from 20 to 30 years, with a mean of 24.3 years. All participants were naïve to the experimental task.

Stimuli and apparatus Participants sat in a dimly lit experimental room with a distance of 70 cm to a 21-in. CRT computer monitor running at a refresh rate of 100 Hz. Stimulus presentation and response collection were done with MATLAB (version 7.10.0.449; The MathWorks, Natick, MA) using the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The stimulus set consisted of alphanumeric characters in the Arial Bold font with a height of 2.6°, presented in red (23 cd/m^2) and blue (13 cd/m^2) on a black (0.2 cd/m^2) background. In each trial, either four or eight characters were distributed randomly at eight predefined locations on an imaginary circle (0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°) with a radius of 7.2° (see Fig. 1). In partial-report trials, four target letters drawn randomly from the English alphabet (excluding C, O, Q, U, W, and Y) were presented with four randomly selected distractor digits from 1 to 9. Control trials consisted of four randomly placed target letters without distractors. Pattern masks were made from crops of Arial Bold characters in the same red and blue hues that were used for the characters.

Design and procedure A keypress started the experiment and initiated the presentation of a fixation cross with a randomly chosen duration of 600, 900, or 1,200 ms, which was followed by a search display with a duration of 100 ms and an immediately subsequent 500-ms mask display. The partial-report trials comprised one half of the experiment, and control trials the other half. In both types of trials, all items were selected without replacement, so that no duplicate elements appeared in the array.

Each search item was either red or blue, and the arrangement of colors made up the following partial-report conditions. In the *sorted-color* condition, targets and distractors were segregated neatly in terms of color (i.e., blue letters and red digits), whereas in the *unsorted-color* condition, the items in each class were presented in both colors. In the *single-color* condition, all items had the same color. In one half of the

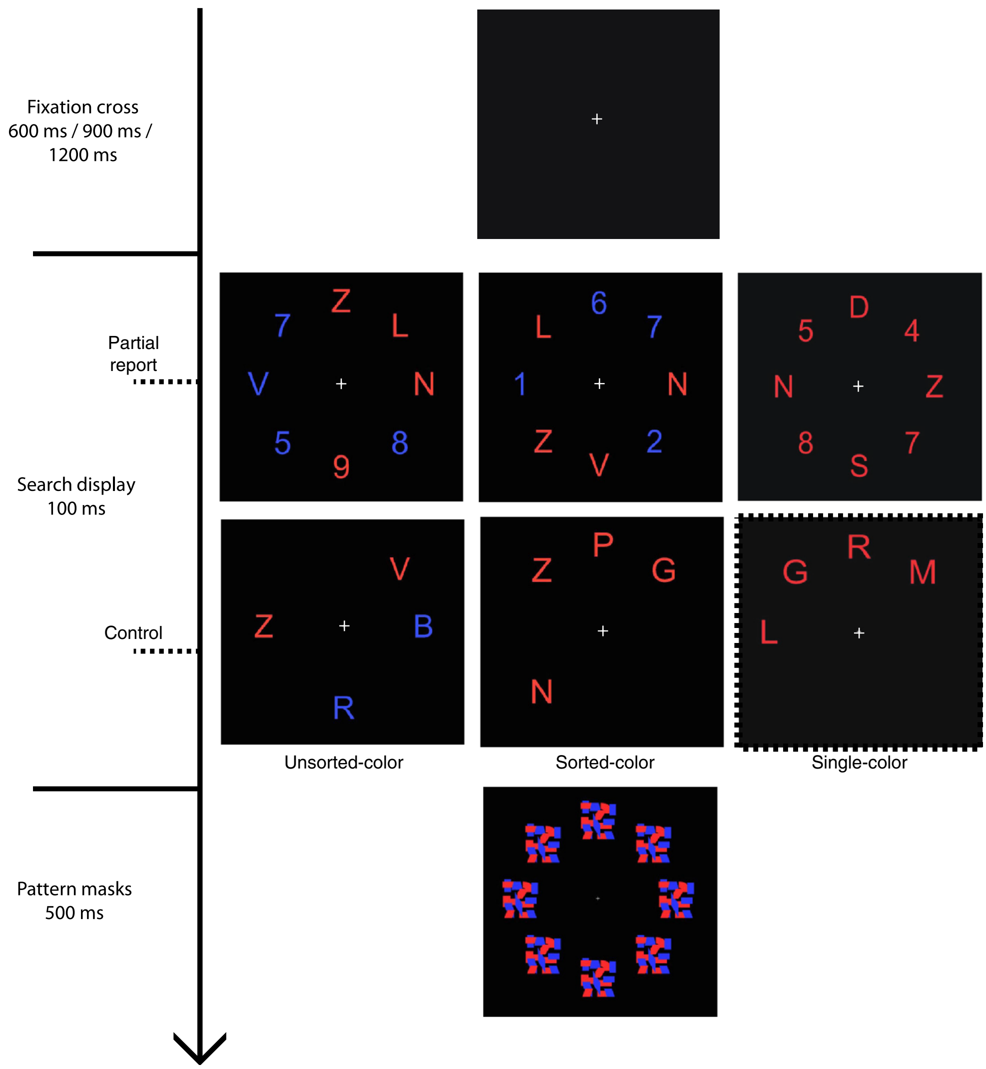

Fig. 1 Illustration of the trial procedure in Experiments 1 and 2. After a fixation cross, a single search display appeared for 100 ms, followed by a mask display. The illustration depicts all possible search display types. Note that the color arrangement and configuration of elements were identical in sorted-color and single-color control trials. The single-color control trials (*dashed outline*) were only presented in Experiment 2

trials the targets were blue, and in the other half the targets were red. For the single-color condition, all items were either red or blue (one half of the trials red, one half of the trials blue). In control trials the color arrangements were the same, although only four target items were displayed.

After a 500-ms pattern mask, participants reported the identities of the target letters, with a maximum possible report of four letters. Responses, in white on a black background, were visible until a fourth letter was entered or until the space bar was pressed. Participants were encouraged to respond only when they felt "fairly certain." The experiment began with a practice block of 100 trials. Accuracy feedback accompanied each individual response, and participants were informed of their mean accuracy for each 100 trials. In all, 120 trials were completed per condition, which added up to 600 trials total. The trial type was randomly drawn without replacement, and trial conditions were randomly intermixed. The duration of the experiment averaged 60 min.

Results

We calculated task performance by counting the number of correctly reported letters per condition and averaging across participants. The performance means for all conditions in Experiment 1, as well as the means from all other experiments in this study, are provided in Table 1. The mean performance levels in control trials showed that participants reported significantly higher numbers of correct letters in the sorted-color condition (M = 2.91) than in the unsorted-color condition (M = 2.78) [$t(14) = 3.87$, $p = .0017$]. Cohen's effect size value ($d = 1.41$) suggested a large effect of search display complexity on performance in control trials.

To measure attentional selectivity, we calculated the cost related to distractor elements by subtracting the average number of correctly reported letters in partial-report trials from the same measure in the corresponding control trials. We attributed the large effect of complexity in control trials to color variation in the search displays: Only a single color was presented in sorted-color control trials, whereas the unsorted-color control trials contained items of both colors. To dissociate the effect of color from the distractor cost, unsorted-color control trials served as the baseline for both the unsorted-color and sorted-color partial-report trials. Conversely, the sorted-color control trials were the baseline for single-color partial-report trials. Figure 2 shows a bar chart of the average distractor costs in each condition. A one-way repeated measures analysis of variance (ANOVA) on distractor costs, applying Complexity (single color, sorted color, unsorted color) as a within-subjects factor, revealed no significant effect [$F(2, 28) = 2.39$, $p = .11$].

Table 1 Mean numbers of correctly reported letters in control (C) and partial-report (PR) trials, as well as the derived distractor cost (DC) measure, broken down by the presentation duration(s) for each experiment

		Exp. 1			Exp. 2			Exp. 3						Exp. 4						Exp. 5					
		100 ms			100 ms			100 ms (small)			100 ms (large)			100 ms			200 ms			200 ms (dark)			200 ms (bright)		
		Sin	Sor	Uns	Sin	Sor	Uns	Sin	Sor	Uns	Sin	Sor	Uns	Sin	Sor	Uns	Sin	Sor	Uns	Sin	Sor	Uns	Sin	Sor	Uns
C	Mean		2.91	2.78	2.90	2.81	2.83		2.26	2.19		2.70	2.59		2.61	2.58		3.20	3.15		3.01	2.91		3.14	3.08
	SE		0.02	0.02	0.05	0.05	0.05		0.03	0.03		0.04	0.04		0.03	0.03		0.03	0.03		0.02	0.02		0.03	0.03
PR	Mean	2.12	2.08	2.06	2.03	2.07	2.12	0.90	0.94	0.91	2.06	2.04	2.01	1.82	1.87	1.83	2.33	2.45	2.30	1.80	1.90	1.60	2.52	2.48	2.18
	SE	0.02	0.02	0.02	0.08	0.07	0.07	0.03	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.02	0.03	0.03	0.03	0.03	0.03	0.03
DC	Mean	0.79	0.70	0.72	0.87	0.77	0.72	1.35	1.25	1.28	0.63	0.56	0.58	0.79	0.74	0.75	0.87	0.76	0.85	1.21	1.01	1.31	0.61	0.60	0.90
	SE	0.04	0.03	0.03	0.07	0.08	0.05	0.04	0.02	0.02	0.05	0.04	0.04	0.03	0.03	0.04	0.03	0.02	0.03	0.03	0.03	0.04	0.05	0.04	0.03

Letters denote the conditions: single-color (Sin), sorted-color (Sor), and unsorted-color (Uns). All associated standard errors (*SE*s) are based on normalized and corrected scores according to Cousineau (2005) and Morey (2008)

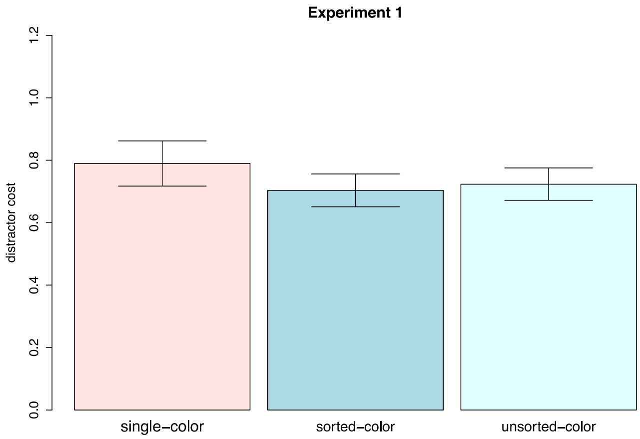

Fig. 2 Bar chart showing the distractor costs (control performance – partial-report performance) in each condition of Experiment 1. The unit on the *y*-axis (distractor cost) is the mean correct letter reports. No differences in distractor cost were significant. The *error bars* here and in subsequent bar charts depict 95% confidence intervals, based on normalized and corrected scores according to Cousineau (2005) and Morey (2008)

Discussion

In this first experiment, participants performed significantly better in the sorted-color than in the unsorted-color control condition. Simply put, participants were less accurate at reporting letters that were not uniformly colored. These trials did not entail visual selection, given that no distractors were present; hence, the performance decrement in unsorted-color trials was not caused by decreased efficiency of selectivity. Rather, it may reflect a cost associated with attentional capture by local feature contrast. An optimal strategy in control trials would be to allocate attention equally to all items. However, the inclusion of differently colored items in the unsorted-color condition may have facilitated an uneven allocation of attention that was suboptimal for such brief exposures.

The level of complexity in the search array, as defined by the relationship between color and alphanumeric class, did not affect the distractor cost. In the sorted-color condition, in which the set of target letters shared one color and the set of distractors shared a different color, we observed no difference in the distractor cost when compared to the unsorted-color condition, in which item color was independent of the selection criterion. This suggests that selectivity was not improved when the targets and distractors were perceptually segregated by color.

Experiment 2: Alphanumeric selection, blocked trials

In Experiment 1, conditions were intermixed and random to the extent that observers were unable to predict whether the color arrangement in the next trial would be unsorted-color or sorted-color. In these circumstances, the optimal strategy might be to stick to the instructions and ignore the color information, even if the organization of color on some trials perceptually segregated the target set from the distractor set.

To investigate the role of attentional control settings in the present paradigm, we performed a second experiment in which the conditions were blocked. If the trial order was consistent, the observers should be able to establish the optimal search strategy, and in the case of the sorted-color condition, incorporate color information into the attentional control settings, which would lead to increased selectivity relative to the unsorted-color condition. The same reasoning would also predict an attenuated effect of attentional capture in control trials.

Method

Participants Eighteen participants (13 female, five male) with normal or corrected-to-normal vision were recruited from the subject pool of the Center for Visual Cognition at the University of Copenhagen. All participants received a monetary reward for participation. Their ages ranged from 20 to 30 years, with a mean of 25.2. All participants were naïve to the experimental task.

Stimuli, apparatus, design, and procedure Experiment 2 was done on the same equipment, with identical settings, and using the same stimuli as Experiment 1. The design and procedure was also copied from Experiment 1, apart from the following changes: Trials were blocked in sequences of 200 trials for each display complexity (single color, sorted color, unsorted color), totaling 600 trials. The order of the complexity blocks was set for each participant according to a two digram-balanced Latin square design. A complexity block contained two blocks of each report type (control, partial report) that alternated, and the initial block was determined by participant number parity. The experiment began with 90 practice trials in blocks of 15 trials. The practice trials shared the same block structure as the rest of the experiment for the given participant.

Results

Performance in control trials did not differ significantly across conditions [$F(2, 34) = 0.99$, $p = .38$], which indicated that color uniformity did not affect performance. Thus, baseline correction of partial-report performance was done within conditions, such that partial-report performance in the single-color condition was subtracted from control performance in the single-color condition, and so forth. Distractor costs were calculated for each condition and averaged across participants (illustrated in Fig. 3). A one-way repeated measures ANOVA on distractor costs, applying Complexity (single color, sorted color, unsorted color) as a within-subjects factor, showed that

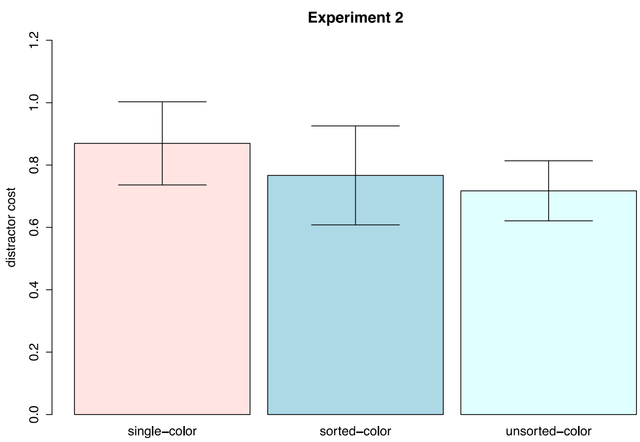

Fig. 3 Bar chart of distractor costs (control performance – partial-report performance) in Experiment 2. As in Experiment 1, distractor costs were not significantly different across conditions

the effect of complexity on the distractor cost was again not significant [$F(2, 34) = 1.43$, $p = .25$].

Discussion

In the control task, the difference in report accuracy observed in Experiment 1 was not present in Experiment 2, which suggests that trial order may have an effect on attentional capture to local feature contrast. It is indeed plausible that the blocked design served to support the adjustment of attentional control settings in each block as hypothesized, and that stimulus driven capture in unsorted-color control trials was inhibited so that an even allocation of attention across all items was successfully maintained.

In addition, search display complexity did not affect selectivity, in that there was no difference between conditions in the costs attributed to added distractors. Thus, the reason for the lack of target grouping benefits in Experiment 1 is most likely not related to top down factors in terms of trial predictability. It may, however, be associated to the relationship between selection criterion and grouping feature dimension. In the study of Jiang et al. (2004), it was speculated that interference of an irrelevant feature in a visual selection task only occurs when the irrelevant feature is closely related to the selection criterion or somehow linked to the task in a general sense. In our Experiments 1 and 2, the selection criterion was alphanumerical class and the grouping feature was color. It is not clear what determines the degree of relatedness of two feature dimensions such as color and alphanumerical class. However, two feature dimensions may be compared with respect to the level of the visual system at which they are processed. Color is a basic feature that is processed in early vision, and a color-defined target will facilitate highly efficient visual search (it will appear to "pop out"; Wolfe & Horowitz, 2004). In contrast, a target defined by alphanumeric class (i.e., a single letter in an array of digits) will not reliably "pop out" (Krueger, 1984), which indicates that letter identification is completed at a later level of processing.

Experiment 3: Selection by size

To test the hypothesis that the irrelevant grouping feature must be closely related to the task-relevant feature for it to modulate performance in the partial-report task, we conducted an experiment in which information relevant for visual selection (i.e., size), as well as information regarding the grouping feature (i.e., color) is processed in early vision. Features such as color and size are processed in early vision whereas processing of alphanumeric class presumably occurs at a later stage. Therefore, we hypothesized that correspondence between selection criterion and grouping feature in terms of processing locus may be a contributing factor to an effect of color grouping on attentional selection.

Method

Participants Fifteen participants (eight female, seven male) recruited from the subject pool of the Center for Visual Cognition at the University of Copenhagen, with a mean age of 24.6 years (range 21–31), participated in exchange for a monetary reward. They all had normal or corrected-to-normal vision. All participants were naïve to the experimental task.

Stimuli, apparatus, design, and procedure The equipment, stimuli, and procedure in Experiment 3 was almost identical to what had been used in Experiment 1. Again, sorted-color trials were defined by color grouping. The following changes were made to the stimuli and structure of the experiment: The search array consisted of letters in two sizes, either large (3.5°) or small (1.7°). An illustration of the size difference can be seen in Fig. 4. In the first half of the experiment, participants reported the identities of letters in one size (e.g.,

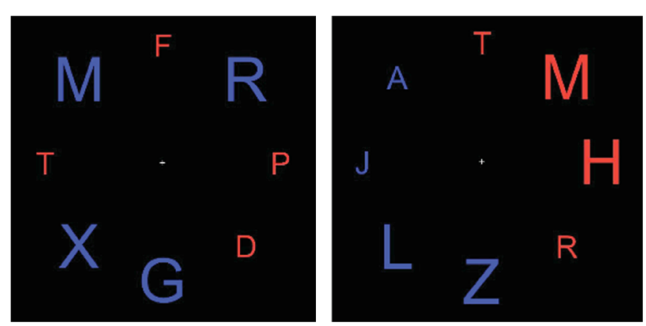

Fig. 4 Illustrated examples of search displays used in the sorted-color (left) and unsorted-color (right) trials in Experiment 3. Large letters subtended 3.5° of visual angle, and small letters subtended 1.7° of visual angle. In one half of the experiment the target letters were large, and in the other half the target letters were small. Apart from these alterations, Experiment 3 was identical to Experiment 1

large), and in the second half they reported the identities of letters in the other size (e.g., small). Participant number determined the target size order, such that every other participant began by selecting large letters, and the other participants began by selecting small letters. The experiment consisted of 700 trials, and the first 100 were practice trials that had the same target size order as the rest of the experiment.

Results

Across both target letter sizes, the accuracy was significantly better in sorted-color control trials (M = 2.48) than in unsorted-color control trials (M = 2.39) [$t(14) = 2.48$, p = .026]. Cohen's effect size value (d = 0.91) suggested a large effect of display complexity on performance in control trials.

Due to the presence of a unicolor superiority effect in control trials, the distractor cost was calculated using the same principle applied in Experiment 1. The derived distractor costs from Experiment 3 (see Fig. 5) were entered into a two-way repeated measures ANOVA with Size (small, large) and Complexity (single color, sorted color, unsorted color) as within-subjects factors. It showed that the main effect of size was significant [$F(1, 14) = 52.90$, $p < .0001$], but that neither the main effect of complexity [$F(2, 28) = 2.61$, $p = .09$] nor the interaction between size and complexity [$F(2, 28) = .07$, p = .93] was significant.

Discussion

In this experiment, we again found no significant effect of task-irrelevant color grouping, in this case with size as the task-relevant feature. The result indicated that even though size, like color, is processed at relatively low levels in the visual system, automatic grouping processes in a different feature domain do not influence selection based on this feature.

Experiment 4: Alphanumeric selection, variable exposure duration

An alternative explanation for the missing effect of color grouping on attentional selection is that the exposure time of 100 ms used in Experiments 1, 2, and 3 was too brief to allow for attentional interactions between processing of different features. Previous studies suggest that grouping effects are constrained to exposures above a certain duration. The shortest exposure duration that facilitated pre-constancy color grouping in the study of Schulz and Sanocki (2003) was 200 ms, and in Jiang et al.'s study (2004) the memory display in the change detection task was presented for 400 ms. Similarly, in a study by Zenon, Ben Hamed, Duhamel, and Olivier (2008), color grouping was observed in a letter search task only when the exposure durations were 360 ms or longer. In

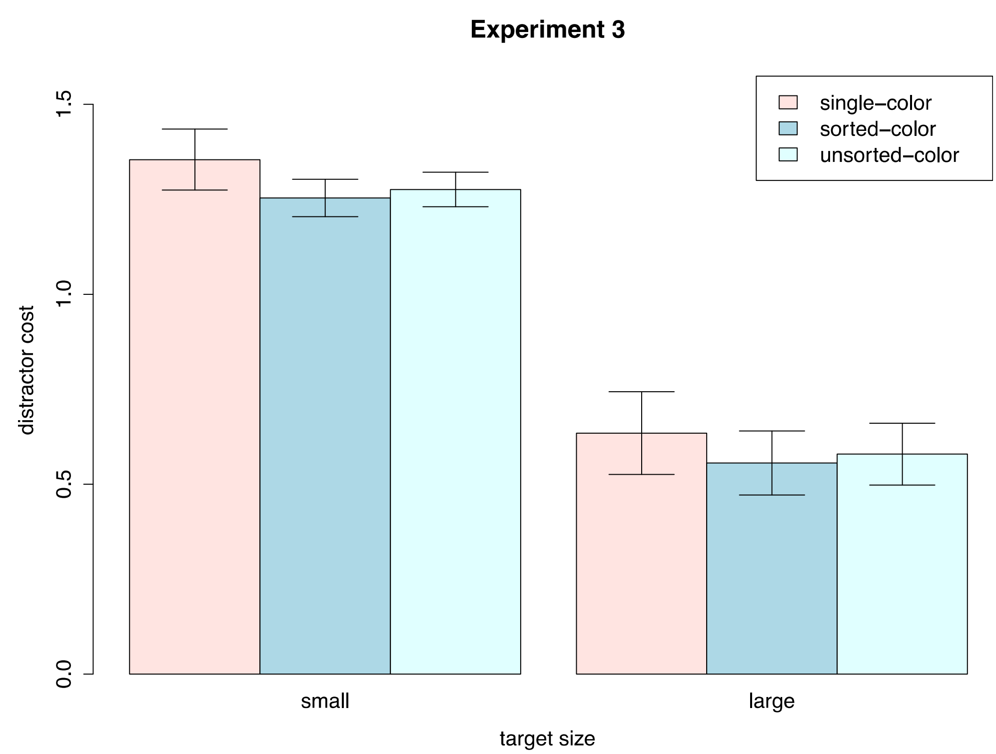

Fig. 5 Bar charts of distractor costs (control performance – partial-report performance) in the three experimental conditions of Experiment 3, in which targets were defined by size. Distractor costs from trials with small letter targets are in the left panel, and distractor costs from trials with large letter targets are in the right panel. Apart from a significant effect of target letter size, as in the previous experiments, distractor costs did not differ significantly across conditions

a study by Kimchi and Razpurker-Apfeld (2004), color grouping of background dots modulated response times in a central change detection task with stimulus exposures of 150 ms. Furthermore, Razpurker-Apfeld and Kimchi (2007) demonstrated that very brief exposures of dots (as short as 40 ms) grouped by lightness or connectedness can elicit priming. However, the prime display in these experiments was not sufficiently masked, in which case the effective exposure duration was higher due to visual persistence. Here we conducted a fourth experiment in which the effect of a longer exposure time, 200 ms, was assessed using the same experimental paradigm as in the earlier experiments.

Method

Participants Fifteen participants (eight female, seven male) were recruited from the subject pool of the Center for Visual Cognition at the University of Copenhagen. Their ages ranged from 18 to 29 years, with a mean age of 24.8. All had normal or corrected-to-normal vision, were naïve to the experimental task, and received monetary payment for participation.

Stimuli, apparatus, design, and procedure In terms of the stimuli, apparatus, design, and procedure, Experiment 4 was mostly identical to Experiment 1. The only difference was that the exposure duration of the search items on one half of the trials was 100 ms, and on the other half of the trials it was 200 ms. The exposure duration of the items in a given trial was drawn randomly, and the participants were not informed of the difference in exposure duration.

Results

Across exposure durations, the mean control performance was higher in the sorted-color condition (M = 2.91) than in the unsorted-color condition (M = 2.86), although this difference was not statistically significant [$t(14) = 1.45$, $p = .17$].

In the absence of a unicolor superiority effect in control trials, distractor costs for each exposure duration were calculated by subtracting partial-report performance from control performance within the unsorted-color and sorted-color conditions. Sorted-color control performance served as the baseline for single-color partial-report performance. A bar chart of the resulting distractor costs associated with the different search display complexities in both exposure durations can be seen in Fig. 6.

A two-way repeated measures ANOVA with Exposure Duration (100, 200 ms) and Complexity as factors yielded no significant main effects of complexity [$F(2, 28) = 2.89$, $p = .07$], and the interaction between complexity and exposure was not also significant [$F(2, 28) = 1.04$, $p = .37$]. The main effect of exposure was also not significant [$F(1, 14) = 2.57$, $p = .13$], but it indicated a cautious trend in the data with respect to exposure duration and the irrelevant color grouping.

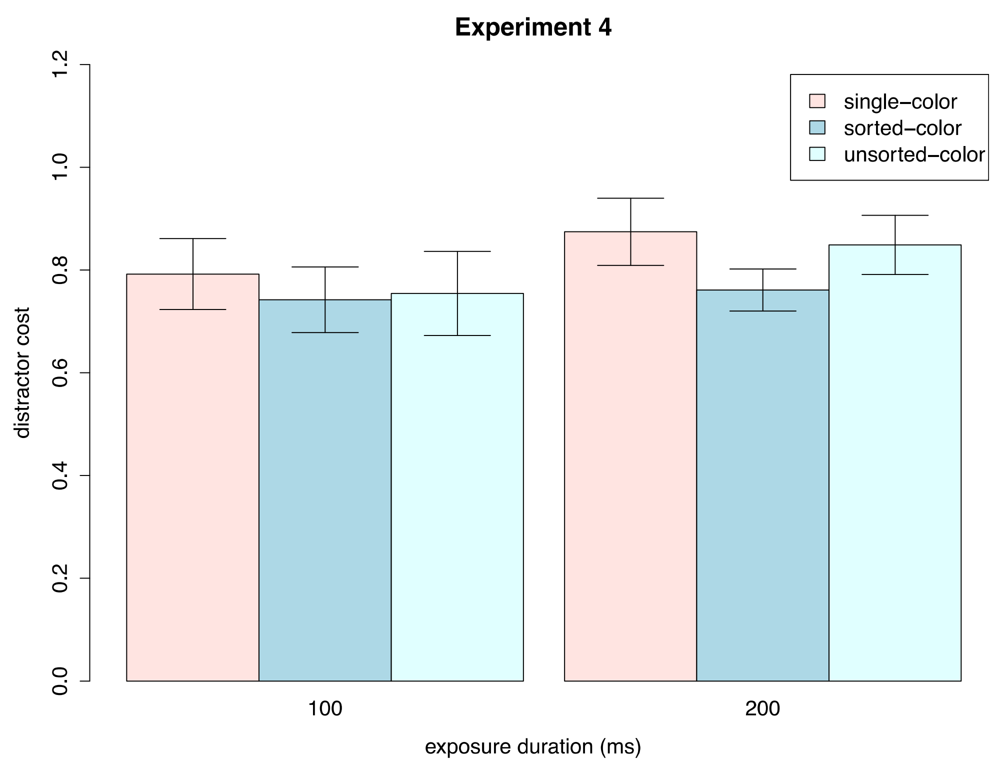

Fig. 6 Bar charts of distractor costs for exposure durations of 100 and 200 ms from Experiment 4. In this experiment, the exposure duration was randomly assigned as 100 or 200 ms in each trial. Search displays in half of the trials had a 100-ms exposure, and search displays in the other half had exposures of 200 ms. We found no significant main effects and no interaction between duration and color condition

Discussion

In this experiment we replicated the null effect found in Experiment 1 with an exposure duration at 100 ms, and also when the exposure duration was 200 ms. Statistics revealed only a slight indication that task-irrelevant color grouping can influence attentional selection when the exposure duration is 200 ms.

Experiment 5: Selection by luminance

In pursuit of demonstrating a stronger and more unequivocal effect of involuntary color grouping, we set up the fifth and final experiment of the study. Here we continued to test at 200 ms, to enhance the possibility of finding an effect, but the crucial manipulation was to test selection based on a feature that should be more closely associated with color than was the size feature used in Experiment 3. Early and recent studies on grouping by either luminance (Fuchs, 1938) or regularity (van den Berg, Kubovy, & Schirillo, 2011) have indicated that the mechanisms that govern these types of perceptual organization are intricately related. Hence, the selection criterion in Experiment 5 was chosen to be luminance.

Method

Participants All participants from Experiment 4 also participated in this experiment. Both experiments were performed on the same day, separated by a 15-min break. Seven of the participants started with Experiment 4, and the rest started with Experiment 5. A monetary reward was also given for participation in this experiment.

Stimuli, apparatus, design, and procedure The experiment was done on the same equipment in the same experimental setting as Experiment 3, and the stimuli, design, and procedure were again the same, except from the following changes. The exposure duration was set at 200 ms, since Experiment 4 indicated that finding effects of perceptual grouping in partial report was more likely at this longer exposure duration. The red and blue letters were presented at two different luminance levels (see Fig. 7 for an illustration). The intensity of the red letters was either *high* (RGB = [0 0 200], 10 cd/m^2) or *low* (RGB = [0 0 50], 0.9 cd/m^2). The blue letter intensities were determined before each experiment through the method of heterochromatic flicker photometry (Kaiser & Comerford, 1975; Wagner & Boynton, 1972) to establish subjective isoluminance between the red and blue letters in the high- and low-intensity categories. In a task that preceded the experiment, participants fixated on the center while eight letters, presented on the positions used in all experiments, alternated between red and blue at 14.2 Hz. Participants regulated the

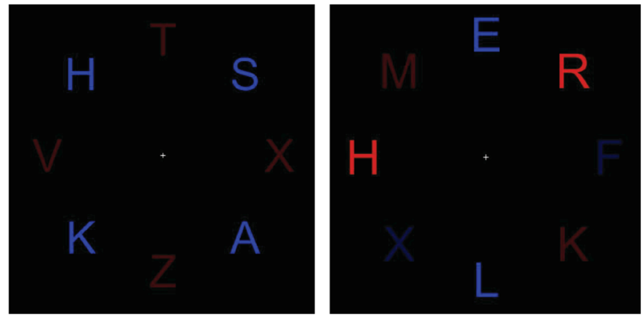

Fig. 7 Illustration of the partial-report search displays used in Experiment 4. The left panel shows the sorted-color condition, and the right panel shows the unsorted-color condition. Target letters were defined by luminance (dark/bright), which shifted halfway through the experiment, so that participants searched for both types of target letters. On the basis of the results from Experiment 4, the exposure duration of the search display was set to 200 ms on all trials

intensity of the blue letters by using the up and down arrows until the apparent flicker was minimized. The starting intensity of the blue letters was randomized. Adjustments were repeated for the high- and low-intensity red letters until ten subsequent responses had a standard deviation less than 15 intensity increments on the RGB scale. The average blue letter intensities were then used in the main experiment.

The control and partial-report search tasks were identical to those in the previous experiments. However, in this experiment the target letters were defined by luminance, such that participants reported as many dark or bright letters as they could, depending on which block they were in. Every other participant searched for dark letters in the first 300 trials and bright letters in the second 300 trials, whereas the remaining participants completed the experiment in the reversed order. As in the previous experiments, sorted-color, single-color, and unsorted-color trials were intermixed randomly. The experiment began with 100 practice trials.

Results

The average control performance in Experiment 5 was significantly higher in the sorted-color condition ($M = 3.07$) than in the unsorted-color condition ($M = 2.99$) [$t(14) = 2.71$, $p = .017$]. Cohen's effect size value ($d = 0.99$) suggested a large effect of display complexity on performance in the control trials. Considering the unicolor superiority effect in control trials, partial-report performance was baseline-corrected by the method applied in Experiments 1 and 2. The distractor costs are illustrated in Fig. 8.

A two-way repeated measures ANOVA of distractor costs with Complexity and Luminance (dark, bright) as factors revealed a significant main effect of complexity [$F(2, 28) = 27$, $p < .0001$]. In this instance the assumption of sphericity was violated, so the p value was Huyhn–Feldt-corrected. The

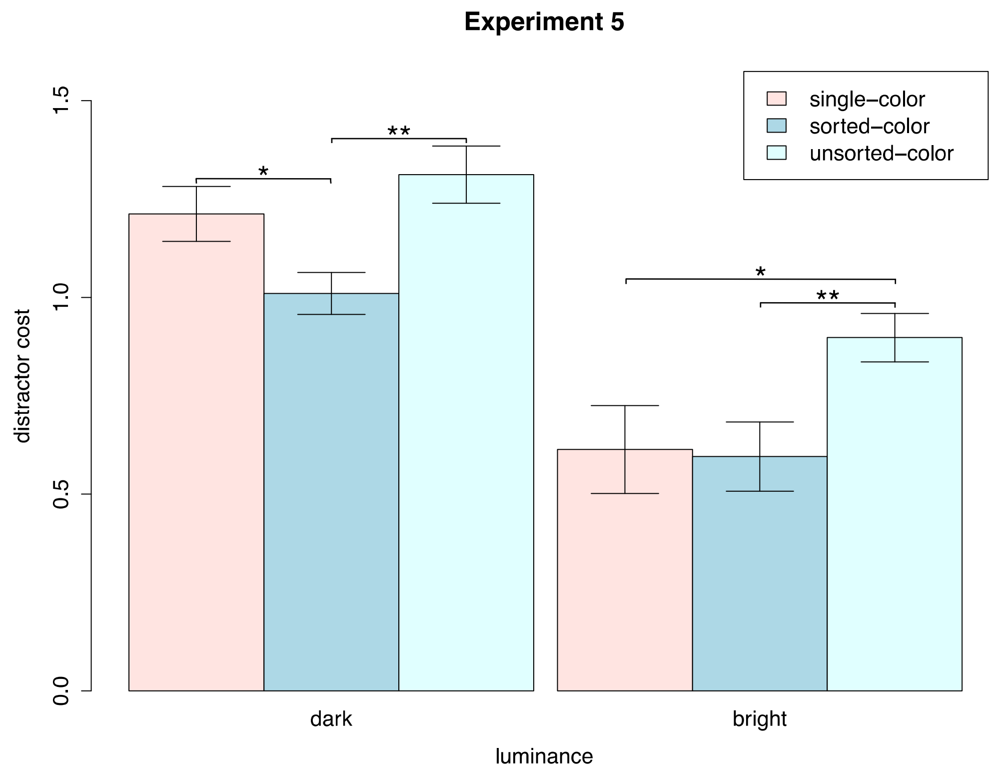

Fig. 8 Bar charts of distractor costs from Experiment 5. In this experiment, participants searched for dark and bright letters in separate blocks. Asterisks indicate $p < .001$, and double asterisks indicate $p < .0001$. Statistical tests here revealed highly significant effects of irrelevant color grouping on search performance

ANOVA also showed a significant main effect of luminance [$F(1, 14) = 35.41$, $p < .0001$]. The interaction between complexity and luminance was also significant [$F(2, 28) = 4.69$, $p = .017$]. Pairwise comparisons for dark target letters showed that the distractor cost was significantly higher in the unsorted-color than in the sorted-color condition [$t(14) = 6.42$, $p < .0001$], and that the distractor cost was not significantly higher in the unsorted-color than in the single-color condition [$t(14) = 1.90$, $p = .078$], whereas the distractor cost was significantly higher in the single-color than in the sorted-color condition [$t(14) = 4.83$, $p < .001$]. In trials with bright target letters, the distractor cost was significantly higher in unsorted-color trials than in both single-color trials [$t(14) = 4.31$, $p < .001$] and sorted-color trials [$t(14) = 6.69$, $p < .0001$], whereas the distractor cost in single-color trials was not significantly different from the distractor cost in sorted-color trials [$t(14) = 4.31$, $p < .001$]. All pairwise tests were corrected for multiple comparisons by the false discovery rate procedure (Benjamini & Hochberg, 1995).

Discussion

In this experiment we found a highly significant effect of task-irrelevant color grouping when attentional selection was based on luminance. The two colors used for each participant were individually calibrated to be subjectively isoluminant, which implies that color was indeed a task-irrelevant feature in this experiment. Still, we found a very clear and highly significant difference in distractor costs between the unsorted-color and sorted-color partial-report conditions for both dark and bright target letters. In our view, the most plausible explanation is that color, although it was objectively task-irrelevant in this experiment, grouped search items into perceptual segments that competed for attention. In sorted-color trials, due to the early processing locus of luminance, the segments holding only targets were rapidly attended, and targets from these segments were encoded into working memory without additional costs. In contrast, when colors were unsorted, competition between color segments was not efficiently resolved, because each perceptual segment contained targets as well as distractors. Thus, additional costs may have been introduced by active suppression of distractors in the entire search display.

General discussion

In the present study we investigated the effect of target grouping by a task-irrelevant feature, color, in the partial-report paradigm. In Experiments 1 and 2 we tested whether color grouping of targets influences performance for targets defined by alphanumeric class when trials were randomly intermixed and when trials were blocked according to grouping condition. The results showed no benefit of the task-irrelevant color grouping in either experiment. Experiment 3 shared the same design as Experiment 1, but the selection criterion was size instead of alphanumeric class. The results from this experiment also revealed no effects of task-irrelevant color grouping on partial-report performance. In Experiment 4 we examined the role of exposure duration in the paradigm, and found no significant changes in performance for color-grouped targets when these were presented for 100 ms. For targets with 200-ms exposures, we also observed no significant differences in performance, and the interaction between exposure duration and search display complexity proved not to be significant. However, the data did show a minor trend toward an effect of exposure duration, and in part motivated by this trend, we conducted a final experiment in which letters were presented for 200 ms and the selection criterion was luminance. In this final experiment the results clearly demonstrated an influence of color grouping on search performance. It is important to note that the colors were balanced perfectly throughout the study, such that the color of an individual item in any given trial never determined whether it was a target or a distractor. As such, the color information specific to individual items was completely irrelevant to the task.

Two main inferences can be drawn from this set of experiments. First, they demonstrate that task-irrelevant target grouping by color improves selectivity in partial report only under certain circumstances. We found that selectivity improves when stimuli are presented at exposure durations of 200 ms, and not when they are presented for 100 ms, which indicates that the color grouping in the present paradigm takes more than 100 ms to fully establish itself. Second, the feature dimension of the selection criterion seems to determine the color-grouping effect, in that improvement is only observed when participants search for luminance-defined targets.

With regard to the temporal sensitivity of the grouping benefit, our results confirm and extend previous findings that perceptual grouping does not always occur at brief exposures (Schulz & Sanocki, 2003; Zenon et al., 2008). To our knowledge, the present study provides the first investigation of color grouping with properly masked stimuli at exposures below 150 ms. Our results indicate that perceptual organization of the visual field in the form of color grouping takes somewhere between 100 and 200 ms to complete. This finding is in line with the extended generalized context model for visual search (Guest & Lamberts, 2011), which emphasizes that similarity relations (e.g., grouping) between visual elements are dynamic and change as perceptual information is accumulated. Further testing will be needed, however, to uncover the exact time course of color grouping.

Earlier findings showed that perceptual grouping can occur without the involvement of attentional processing (Lin & Yeh, 2016; Shomstein, Kimchi, Hammer, & Behrmann, 2010; Stuit, Paffen, van der Smagt, & Verstraten, 2011). In Experiment 5, we found that distractors were less disruptive in a sorted-color color arrangement. A possible explanation may be that, because of preattentive perceptual grouping, same-colored elements automatically group together and form separate perceptual segments or groups. As a result, attention may then be allocated to groups of elements (e.g., all blue letters). In the sorted-color trials in Experiment 5, each color segment was either full of distractors or full of targets, which means that the primary task of the visual system in this case was to determine which segment held the targets. Once attention was allocated to the target segment, individual elements might be encoded into working memory without any additional noise from distractors. In the unsorted-color trials, however, the color grouping was incompatible with the selection criterion. Each segment contained both targets and distractors; thus, to prevent erroneously encoding items, distractors had to be suppressed within each color-defined group, which was reflected in an increased distractor cost. Single-color trials had only same-colored elements, so the entire display constituted a single perceptual segment, and as in unsorted-color trials, distractor suppression on the entire set of search items was required, which may explain the rise in distractor cost levels that we observed in this condition in dark-letter-target trials. This increase in distractor costs for single-color trials was not present when the target letters were bright (as illustrated in Fig. 8), presumably because target selection was relatively effortless, and nothing was to be gained from a sorted-color display.

The selection criterion in Experiment 5 was luminance (e.g., search for dark letters), and an item characterized by luminance is most likely processed in preattentive vision, whereas the processing of an item characterized by alphanumeric class probably takes place at a later stage (Wolfe & Horowitz, 2004). Therefore, the mechanisms of perceptual grouping had different implications in Experiment 5 than in the experiments in which participants searched for letters amongst digits. When the selection criterion was alphanumeric, color grouping may proceed independently of activation of the filters necessary for discriminating between digits and letters. In Experiment 3 the selection criterion was size, and because of its presumably early processing locus, we predicted that size selection would interfere with color grouping, resulting in a difference in distractor costs. This was not observed, however, and we believe there are two possible explanations for this. First, it may be that the relationship between luminance and color is closer than that between size and color. In an early study of Gestalt principles, Fuchs (1938) found that luminance grouping can alter color appearances. Callaghan (1984) also found that luminance variation interfered with hue discrimination under most experimental conditions. Similarly, a more recent finding has suggested that grouping by regularity may interfere with perceived luminance (van den Berg et al., 2011). Thus, it is possible that color grouping in the unsorted-color trials of Experiment 5 complicated the luminance search by altering the perceived luminance. On the other hand, it is not likely that color grouping affected the perception of size in Experiment 3, which would explain the absence of a grouping effect on distractor costs in that experiment. Second, one important difference between Experiments 3 and 5 was the exposure duration of the search array. Extending the processing time to 200 ms may have been crucial in producing the observed color grouping effect. Unfortunately, it is not possible on the basis of this study to determine whether prolonged exposure of a size-sorted search array would produce a color-grouping effect similar to the one seen in Experiment 5. For this question to be settled, further studies will be needed.

Our account of the results of this study includes a division of attentional processing into an early, preattentive stage and later, attentive stages. As such, the present evidence is consistent with the Guided Search model (Wolfe, 1994, 2007), which similarly distinguishes between preattentive and attentive vision. According to this model, basic features that can guide attention and facilitate efficient search are extracted in preattentive vision. In addition, information about the global configuration of visual elements is processed preattentively. The processing of such information is not specific to certain feature values, and is thus denoted as *nonselective processing* in later revisions of Guided Search (Wolfe, 2007; Wolfe, Võ, Evans, & Greene, 2011). The alternative, nonselective pathway was originally conceived to account for effects of contextual analysis in natural-scene search (Torralba, Oliva, Castelhano, & Henderson, 2006), and this has been supported by evidence of efficient scene search among expert radiologists (Drew, Evans, Võ, Jacobson, & Wolfe, 2013). The effects of perceptual grouping that we found in Experiment 5 seem to suggest that nonselective processing also includes perceptual organization, such as color grouping.

Conclusion

In this study we tested whether task-irrelevant color grouping of targets affects the efficiency of attentional selection in the partial-report paradigm. In Experiment 1, in which the trial order was randomly intermixed, we found no effects of task-irrelevant color grouping on performance when the selection criterion was alphanumerical class and the exposure duration was 100 ms. This result was replicated in Experiment 2, in which trial order was blocked. A similar null effect was found in Experiment 3, in which the selection criterion was size and the exposure duration was again 100 ms. In Experiment 4, in which the selection criterion was alphanumeric class and the exposure duration varied, we also found that selectivity was not improved when the display items were sorted-color with respect to the selection criterion. Interestingly, in Experiment 5 we found a pronounced effect of the irrelevant color grouping of targets when the selection criterion was luminance and the exposure duration was 200 ms. In addition to improved selectivity for displays in which target letters were grouped by color, we found impaired selectivity for unsorted-color displays. Taken together, these results suggest that the benefit of task-irrelevant color grouping of targets is contingent on the processing locus of the selection criterion.

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