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Visual attention is a single, integrated resource

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ABSTRACT

Recent evidence for separate forms of attention for different visual attributes seems to conflict with Duncan's "integrated competition" theory of visual attention. To resolve this conflict, we established attention-operating characteristics for four pairs of visual discriminations. While one task was common to every pair, the other tasks were different and concerned different visual attributes. In all pairs, the common task exhibited the same performance-resource function, whether the other tasks involved entirely similar, partially similar, or entirely dissimilar visual attributes. These results confirm that visual attention conforms exactly to the predictions of a single, integrated resource.

1. Introduction

When two visual objects are presented briefly and simultaneously, observers often readily report an attribute of either object, but find it difficult to report attributes of both. The constraint that observers experience in this situation defines the "limited resource" of visual attention (e.g., Pashler, 1999). The allocation of this "resource" is under voluntary control and observers are able to increase report accuracy for one object at the expense of decreasing response accuracy for the other (Norman & Bobrow, 1975; Sperling & Dosher, 1986). This trade-off in the accuracy of competing reports is known as the "attention-operating characteristic" (Sperling & Melchner, 1978) and provides our only quantitative measure of attentional "resources".

Over the years, numerous attention-operating characteristics have been reported for pairs of simple visual discriminations. Comparing these reports, one is struck by the extreme range of outcomes: some pairs of discriminations conflict severely, other pairs conflict hardly at all, and yet others conflict to some degree (Bonnel & Prinzmetal, 1998; Braun, 1994, 1998; Braun & Julesz, 1998; Braun & Sagi, 1991; Duncan, 1984; Joseph, Chun, & Nakayama, 1997; Lee, Itti, Koch, & Braun, 1999; Lee, Koch, & Braun, 1999b; Li, VanRullen, Koch, & Perona, 2002; Morrone, Denti, & Spinelli, 2002, 2004; Pastukhov & Braun, 2007; Reddy, Reddy, & Koch, 2006; Reddy, Wilken, & Koch, 2004; Saenz, Buracas, & Boynton, 2003; Tsuchiya & Braun, 2007). This is true even though the investigated situations are nominally comparable with brief presentation times, limited visual persistence, binary response choices, and similar response accuracies for the individual discriminations.

It is well established that the object-based nature of attentional selection may lessen or altogether avoid the conflict between concurrent visual discriminations (Blaser, Pylyshyn, & Holcombe, 2000; Driver & Frith, 2000; Duncan, 1996; Reynolds & Chelazzi, 2004; Roelfsema, Lamme, & Spekreijse, 1998; Scholl, 2001; Treisman & Kanwisher, 1998). When the discriminated attributes are perceptually grouped into a single visual object, response accuracies remain high and little or no trade-off is observed. However, it is difficult to see how object-based selection could explain the varied outcomes of the paired discriminations mentioned above. For many of the cited studies employed spatially distant and visually disparate attributes (e.g., foveally presented letters and peripherally presented natural scenes) offering no evident basis for perceptual grouping.

Another possible reason for a reduced conflict between concurrent discriminations is that there may exist different kinds of attentional resources (Norman & Bobrow, 1975; Sperling & Dosher, 1986). If attentional resources were "differentiated" in this way, one would expect more severe conflicts for pairs of similar discriminations (which would draw more on the same resources) than for pairs of dissimilar discriminations (which would draw less on the same resources). Early comparisons of similar and dissimilar pairs of discriminations reported comparable degrees of conflict (Duncan, 1993; Duncan & Nimmo-Smith, 1996; Ward, Duncan, & Shapiro, 1997). Later studies corroborated this view, demonstrating identical conflict between similar and dissimilar pairs of both

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resource-demanding and less resource-demanding discriminations (Lee, Koch, & Braun, 1999a, 1999b). More recently, however, it has been reported that discriminations of luminance and color draw on distinct attentional resources (Morrone et al., 2002, 2004; see also VanRullen, Reddy, & Koch, 2004).

Of course, the varied outcomes of concurrent-discrimination studies may simply reflect the different attentional demands of different types of discriminations (Braun, 1998, 2008; Braun, Koch, Lee, & Itti, 2001). In this case, two concurrent discriminations would conflict only to the extent that their combined demands exceed the available resource (Norman & Bobrow, 1975). The difficulty with this interpretation is that it would assign a disconcertingly small attentional demand to many discriminations. This is because one observes little or no conflict with numerous asymmetric task pairs, in which one task places maximal demands on attention (Braun, 1998; Braun & Julesz, 1998; Lee, Itti, et al., 1999; Li et al., 2002; Tsuchiya & Braun, 2007). Accordingly, the assumption of a single, undifferentiated attentional resource conflicts with the widely held position that a visual discrimination and the associated voluntary response always impose a non-negligible attentional cost (Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006; Joseph et al., 1997; O'Regan & Noe, 2001; Posner, 1994; Treisman & Kanwisher, 1998).

Here we ask whether the attention demand of a visual discrimination remains the same or whether it changes when paired with other discriminations involving various stimuli and attributes. If task pairs with varying degrees of conflict (from severe to small) yield a consistent attention demand for the discrimination that is common to all pairs, it would strengthen the case for an undifferentiated attentional resource. If the attention demand changes from pair to pair, it would argue for a differentiated nature of attentional resources.

For four task pairs, we established the attention-operating characteristic by dividing attention in different proportions between two discriminations. In each case, we inferred how response accuracy rises with the proportion of attention allocated to each of the two discriminations (Lee et al., 1999b). For the discrimination common to all pairs, we obtained the same relationship between attentional allocation and response accuracy in all experiments. Thus, our findings provide further evidence that visual attention is undifferentiated.

2. Methods

2.1. Observers

Procedures were approved by the Medical Ethics Board of the University of Magdeburg and informed consent was obtained from all observers. All observers had normal or corrected-to-normal vision. Apart from the first two authors, who also participated in study, observers were naïve as to the purpose of the experiment and were paid for participation.

2.2. Apparatus

Stimuli were generated by computer (video card Quattro FX 1100, NVidia, Santa Clara, CA) and displayed on a 19″ screen with a refresh rate of 85 Hz and a resolution of 1600 × 1200 (Vision Master Pro 454, Iiyama Corporation, Nagano, Japan). At an eye-screen distance of 95 cm, each pixel subtended approximately 0.015°. Screen luminance was calibrated with a luminance meter and color-bit-stealing was used to create small luminance steps (Tyler, 1997). The background luminance of our displays was 4.5 cd/m^2.

Small eye movements cannot be ruled out when viewing a moving stimulus (like those used in experiments with moving plaid and rotating ellipse), known to induce optokinetic nystagmus even for brief stimulus presentations (Kommerell & Thiele, 1970). To counter-act this, observers were instructed to fixate on a stationary dot at the display center, a measure known to suppress OKN and significantly reduce residual eye movements (Pola, Wyatt, & Lustgarten, 1995). Additionally, the brief presentation times coupled with the concentric layout of possible target locations rendered voluntary eye movements to peripheral locations counterproductive.

2.3. General procedure

In each experiment, the target display contained central and peripheral targets that were presented concurrently. Instructions defined separate and independent discrimination tasks with respect to each target type (“central” and “peripheral tasks”). The response order was fixed and observers reported first on the *central* and second on the *peripheral task*. Responses were not speeded and instructions emphasized response accuracy. The relative priority afforded to each task was manipulated by additional instructions. In separate blocks of trials, observers were asked to either give priority to the *central task*, the *peripheral task*, or equal priority to both tasks (*dual-task performance*). In yet further blocks of trials, observers performed only one task and ignored the other (*single-task performance*). Each block consisted of 50 trials.

When observers discriminated target color, the visual persistence of target displays was curtailed by masking. Effective masking forces observers to divide attention between central and peripheral targets and maximizes dual-task interference (Lee et al., 1999b). The mask displays used in the present study were similar to those employed in previous work (Braun & Julesz, 1998). In addition, their efficacy was confirmed by establishing psychometric functions under *single-task conditions* (not shown). The time between stimulus and mask onset (stimulus-onset asynchrony, SOA) was chosen such that each observer achieved approximately 80% performance under *single-task conditions*.

In other previous work (Lee et al., 1999b; Pastukhov & Braun, 2007; Tsuchiya & Braun, 2007), we found that visual persistence poses little or no problem when observers discriminate visual motion. In this case, complete dual-task interference is observed even without masking. Accordingly, no masking was used for moving targets. Other display parameters were used to ensure that each observer achieved approximately 80–90% performance under *single-task conditions*.

2.4. Central task

A set of seven rotating dumbbell shapes (set diameter 1.5°) was presented for 200 ms (Fig. 1F). Each dumbbell rotated with a frequency chosen randomly between 1.5 Hz and 3.5 Hz. Dumbbells rotated both clockwise and counter-clockwise and the prevailing sense of rotation was chosen randomly for each set. Observers reported the prevailing sense of rotation of the set, pressing ‘J’ for “mostly clock-

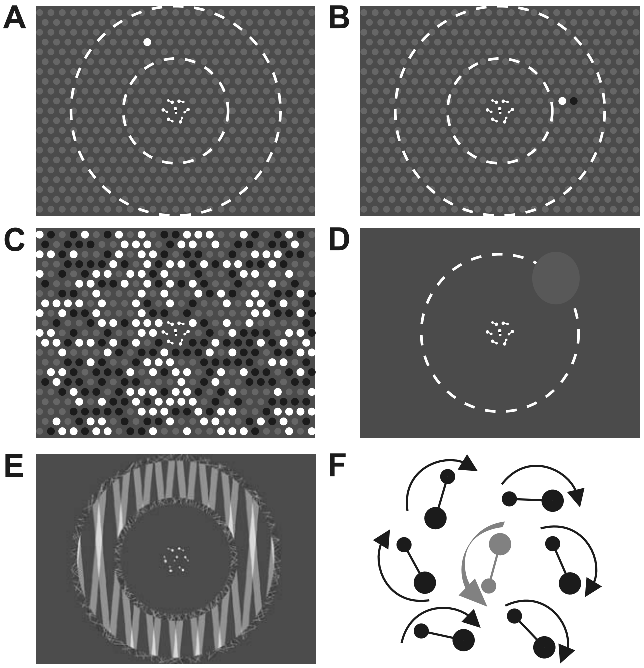

Fig. 1. Stimulus displays, schematic. (A) Color discrimination task. Dashed lines mark boundaries of possible target locations. The target (here shown white) was either red or green and equiluminant with gray distracters. Observers reported target color. (B) Color-position discrimination task. The targets (here shown white and black) were red and green. Observers reported relative position of the two targets. (C) Mask for color-identity and color-position tasks. (D) Rotating ellipse task. Dashed line shows possible ellipse locations. Observers reported rotational sense of the ellipse. (E) Moving plaid stimulus. Observers reported direction of motion (vertical or horizontal). (F) Rotating dumbbells of central task. Observers reported the predominant rotational sense.

wise” and ‘F’ for “mostly anti-clockwise”. One to three dumbbells rotated in the opposite sense. This number was chosen for individual observers and controlled task difficulty.

2.5. Peripheral task 1: Color discrimination

In this experiment, a dense texture of gray discs (*distracters*, radius 0.3°, luminance 9 cd/m^2) filled the periphery of the display on a hexagonal grid (distance between elements—1°), see Fig. 1A. A single colored disk (target, isoluminant red or green) appeared at a grid location in an annular region of the display (inner radius 9°, outer radius 14.5°). Flicker photometry was used to choose target colors for each observer that was subjectively isoluminant with the distracters. Observers reported target color pressing “left” for a red and “right” for a green target. The target array was presented for 20 ms and was followed by a blank period (range 30–60 ms) and by a mask array of 80 ms duration (Fig. 1C). The mask array contained gray, red, and green disks in equal proportion. The time from stimulus to mask onset (stimulus-onset asynchrony, SOA) was chosen for each observer to ensure approximately 80% performance in the *single-task condition*.

2.6. Peripheral task 2: Color-position discrimination

This peripheral task also involved a hexagonal array of gray discs. Two colored target discs appeared at horizontally adjacent locations in an annular region around display center (inner radius 9°, outer radius 14.5°), see Fig. 1B. Observers discriminated the relative position of the two targets and reported ‘left’ when the red disc was to the left of the green disc and ‘right’ otherwise. The mask array (Fig. 1C) and presentation schedule were identical to the previous experiment. The SOA was chosen individually for each observer to ensure approximately 80% performance under single-task conditions (range 70–90 ms).

2.7. Peripheral task 3: Rotating ellipse

Here, the peripheral target was a rotating ellipse (major and minor axis 2.7° and 2.4°, respectively), which appeared for 200 ms at a randomly chosen locations of 6° eccentricity (Fig. 1D). Observers reported the direction of rotation, pressing ‘left’ for counter-clockwise and ‘right’ for clockwise rotation. Rotation speed (observer average of 0.6 cps) was chosen for each observer to obtain a task performance of approximately 90% correct under single-task conditions.

2.8. Peripheral task 4: Moving plaid

This task concerned a moving plaid (Adelson & Movshon, 1982) that filled an annular region (inner radius 9°, outer radius 14.5°), with visible apertures (diameter 0.5°, 10% contrast) to minimize the visual impact of terminators (Fig. 1E). Each component grating was a square wave grating (2.2 cycles/deg spatial frequency, duty cycle 0.3, contrast 50%). The contrast of intersections was computed with an additive transparency rule. The angle between component gratings was either 170° or 178° and was chosen for each observer to ensure that the plaid was reliably perceived either as a single coherent pattern moving upwards or as two transparent patterns moving sliding sideways across each other. Control experiments confirmed that observers based their reports on perceived motion rather than perceived form: static plaids with the same angular difference were significantly less discriminable (Pastukhov, Festman, & Braun, 2004). Presentation time (range 150–200 ms) and gratings’ speed (range 0.5–2°/s) was chosen for each observer to obtain a task performance of approximately 90% correct under single-task conditions. Observers discriminated between the two kinds of plaid motion, pressing ‘left’ for the transparent plaid and ‘right’ for the coherent plaid.

2.9. Performance measure

All tasks involved the discrimination of two stimulus alternatives, A and B. Fractions of correct responses f_A and f_B were obtained for each stimulus alternative and combined to yield a representative performance value p_{AB}

$$p_{AB} = 100\% F\left(\frac{1}{2}F^{-1}(f_A) + \frac{1}{2}F^{-1}(f_B)\right), \tag{1}$$

$$F(z) = \frac{1}{\pi}\int_{-\infty}^{z} e^{-t^2}\,dt, \tag{2}$$

where $F^{-1}()$ denotes the inverse function of the normal distribution $F(z)$. This performance value is independent of observer criterion and corresponds to the discriminability d' expressed in units of percentage correct.

To facilitate the comparison of different observers, all performance values p_{AB} for a particular observer/task were normalized with respect to the average single-task performance for this observer/task, p_{AB}^{single}. All illustrations are based on normalized performance P:

$$P = 100\% \frac{p_{AB}}{p_{AB}^{single}}. \tag{3}$$

2.10. Attention-operating characteristics and performance-resource functions

To analyze dual-task results, we postulated for each task a monotonically increasing performance-resource function (PRF), of the form

$$p(r) = \begin{cases} \frac{p(1)}{2}\left(\frac{2r}{\alpha}\right)^{\beta} & \text{if } 0 \leqslant r \leqslant \frac{\alpha}{2} \\ p(1) - \frac{p(1)}{2}\left(\frac{2(\alpha - r)}{\alpha}\right)^{\beta} & \text{if } \frac{\alpha}{2} < r \leqslant \alpha \\ p(1) & \text{if } \alpha < r \leqslant 1, \end{cases} \tag{4}$$

where $p(r) \in [0,1]$ is performance as a fraction of the interval between chance (defined as 0) performance and single-task performance (defined as 1), $r \in [0,1]$ is the fraction of attention allocated to the task, and $p(1)$ is the maximal performance (single-task performance or performance with full attention). The parameter α determines the fraction of attention that suffices for maximal performance. The parameter β ($\beta \geqslant 1$) determines the linearity of the monotonic relation between attention and performance ($\beta = 1$: linear, $\beta = 2$: quadratic, etc.). For further details, see Lee et al. (1999b). The attention-operating characteristic (AOC) is the curve [$p_{central}(r)$, $p_{peripheral}(1-r)$]. To fit a given set of observations, we choose the AOC that maximizes the a posteriori likelihood of these observations. For each set of parameters $\alpha_{central}$, $\beta_{central}$, $\alpha_{peripheral}$, $\beta_{peripheral}$, we calculated the likelihood of a given observation ($P_{central}$, $P_{peripheral}$), from normal distributions with means given by the closest AOC point, [$p_{central}(r)$, $p_{peripheral}(1-r)$], and variances given by the empirical single-task variance ($\sigma_{central}$, $\sigma_{peripheral}$).

2.11. Response contingencies

In a dual-task situation, the division of attention may be consistent throughout a block of trials or it may vary from trial to trial (Sperling & Dosher, 1986). These alternatives may be distinguished by analyzing the joint probabilities of responding correctly and/or incorrectly on each task (Braun & Julesz, 1998). If the division of attention remains constant, success or failure on one task will be independent of success or failure on the other task. If the division of attention varies, one expects a negative correlation. We used a χ^2 test to test for statistically significant (negative) correlations between the responses accuracies of the two tasks.

3. Results

In four experiments, we combined the same central task with four different peripheral tasks, establishing in each case the attention-operating characteristic for the task combination and the performance-resource functions for both component tasks. The peripheral tasks were chosen to impose different attentional demands (low or high) and to involve different stimulus attributes (color or motion and/or relative position). In this way, we determined the performance-resource function of the central task four times (i.e., based on four independent data sets). The aim was to ascertain whether the central task poses the same attentional demand when combined with different concurrent tasks, or whether its attentional demand varies with the task combination.

3.1. Experiment 1: Color discrimination

The first experiment combined the central task with a peripheral task posing a modest attentional demand (Braun & Julesz, 1998): observers discriminated the color of a target disk in a dense array of non-colored distracters (Fig. 1A). Visual persistence was curtailed by a mask array (Fig. 1C).

Four observers performed 73 and 60 blocks under *single-task* and *dual-task* conditions, respectively. A contingency analysis of the pooled dual-task data showed no significant (negative) correlations between central and peripheral task accuracy for any observer (χ^2 = 1.87, critical value for 95% confidence interval = 3.8), demonstrating that observers divided attention consistently throughout each block of trials. Fig. 2A shows the combined results of all observers in the format of an attention-operating characteristic (AOC). Dual-task data was collected with different instructions concerning the priority to be afforded to each task (see Section 2). The dual-task results, which are presented as gray, white, or black circles depending on instructions, delineate the performance trade-off between central and peripheral tasks: as performance improves on one task, it worsens on the other.

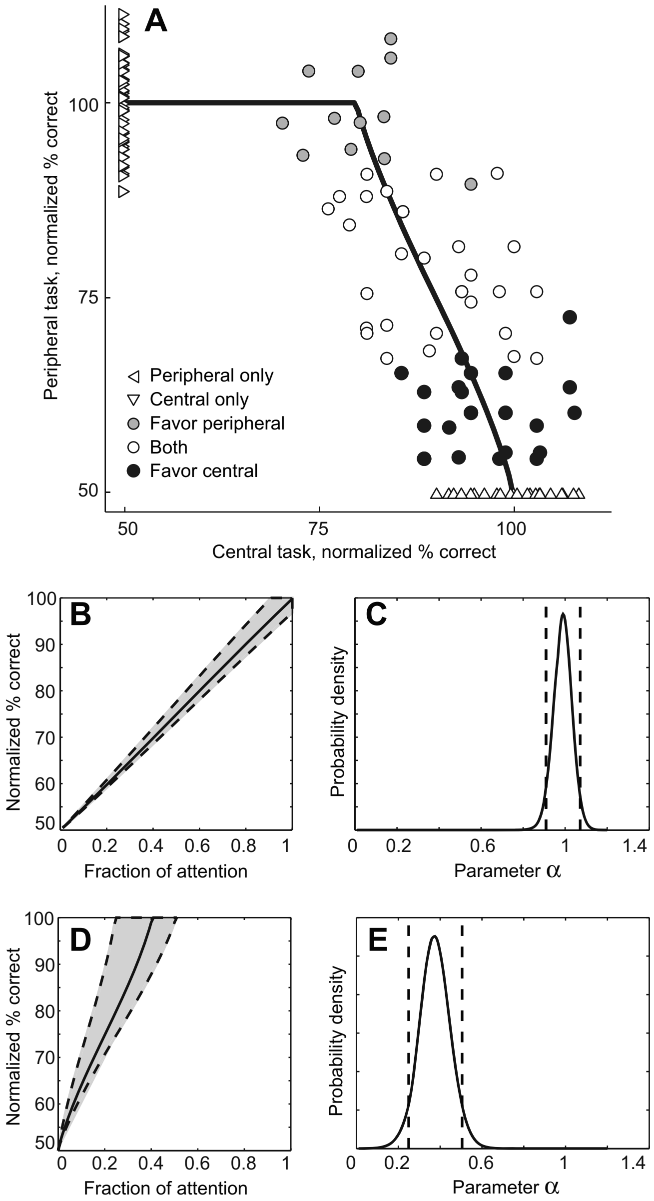

Fig. 2. Experiment 1: Color discrimination. (A) Results from 31 blocks central task only (single-task, triangles), 42 blocks peripheral task only (single-task, triangles), and 60 blocks of both tasks together (dual-task, circles). Shading of circles (white, gray, black) denotes different dual-task instructions (priority to the central task, priority to the peripheral task, or equal priority to both tasks, see Section 2). Dual-task results are fitted with an attention-operating characteristic (solid line). (B) Family of well-fitting performance-resource functions for central task ($p = .05$). (C) Likelihood distribution of parameter α_{central}. (D) Family of well-fitting performance-resource functions for peripheral task ($p = .05$). (E) Likelihood distribution of parameter $\alpha_{\text{peripheral}}$.

The present task combination is characterized by an asymmetric trade-off in performance. When the peripheral task is performed optimally, central-task performance is still near 75% correct. However, when the central task is performed optimally, peripheral task performance is near chance. The implication is that optimal performance of the central task requires full or almost full attention, while optimal performance of the peripheral task is possible with less than full attention. To quantify this conclusion, we fitted two performance-resource functions (PRFs) to the AOC data, using a maximum-likelihood approach (see Section 2). The most likely combination of PRFs to have produced our observations is shown in Fig. 2B and D, together with the 95% confidence range around each PRF.

The "attention demand" of each task is represented by parameter α, which is the smallest fraction of attention consistent with optimal performance. For the central task, the most likely value of α was 99% and the 95% confidence range was $\alpha > 92\%$ (Fig. 2C). For the peripheral task, the inferred value of α fell near 37% (95% confidence interval between 25% and 50%). In earlier work, the attention demand of a similar color discrimination tasks was found to be near 30% (Lee et al., 1999b).

3.2. Experiment 2: Color-position discrimination

In the second experiment, we combined the same central task with a modified peripheral task that we expected to demand full attention. Although in general the discrimination of multiple target colors poses only a modest attention demand (Braun & Julesz, 1998), attentional requirements increase dramatically for targets in close spatial proximity (Lee et al., 1999b). Apparently, the discrimination of the precise relative position of two colored targets requires considerable attention. In view of these previous results, we modified the peripheral task by adding a second colored target and by asking observers to report the relative position of the red and green target (Fig. 1B). As before, visual persistence of the peripheral target array was curtailed by masking (Fig. 1C).

Four observers performed 34 and 44 blocks under *single-task* and *dual-task* conditions, respectively. A contingency analysis of the pooled dual-task data revealed no significant (negative) correlations between central and peripheral task accuracy for any observer ($\chi^2 = 1.63$, critical value for 95% confidence interval = 3.8).

Fig. 3A shows the combined results of all observers. For this modified task combination, the trade-off between central and peripheral performance is symmetrical and task interference is complete: when either task is performed optimally, the other task is performed at or near chance. Qualitatively, this pattern of results implies that both tasks require full attention for optimal performance. The quantitative analysis in terms of fitted PRFs bears out this interpretation (Fig. 3B and D). For the central task, the most likely attention demand was $\alpha = 107\%$ (range $\alpha > 86\%$, Fig. 3C), essentially identical to value of $\alpha = 99\%$ (range > 92%) determined in Experiment 1. For the peripheral task, the most likely attention demand was $\alpha = 102\%$ (range $\alpha > 89\%$, Fig. 3D) and therefore dramatically higher than in Experiment 1.

These results are consistent with the possibility that the attentional demand of the central task is fixed and does not change in different task combinations. In addition, these results confirm the high attentional demand of discriminating the relative position of two colored targets in close proximity (Lee et al., 1999b).

3.3. Experiment 3: Rotating ellipse

The third experiment paired the central task with a peripheral task concerning visual motion. Specifically, we chose the discrimination of rotary motion, as previous work shows this to impose a large attention demand (Lee et al., 1999b). In contrast, the discrimination of linear motion often requires little or no attention (Tsuchiya & Braun, 2007; see also Experiment 4). The peripheral target was a large, slowly rotating ellipse (Fig. 1D), and observers discriminated the direction of rotation (clockwise or counter-clockwise). No masking was used and task difficulty was controlled by adjusting the speed of rotation.

Four observers performed 117 *single-task* and 247 *dual-task* blocks. The contingency analysis revealed no significant (negative) correlations between central and peripheral task accuracy ($\chi^2 = 2.86$, critical value for 95% confidence interval = 3.8). The combined results are shown in Fig. 4A.

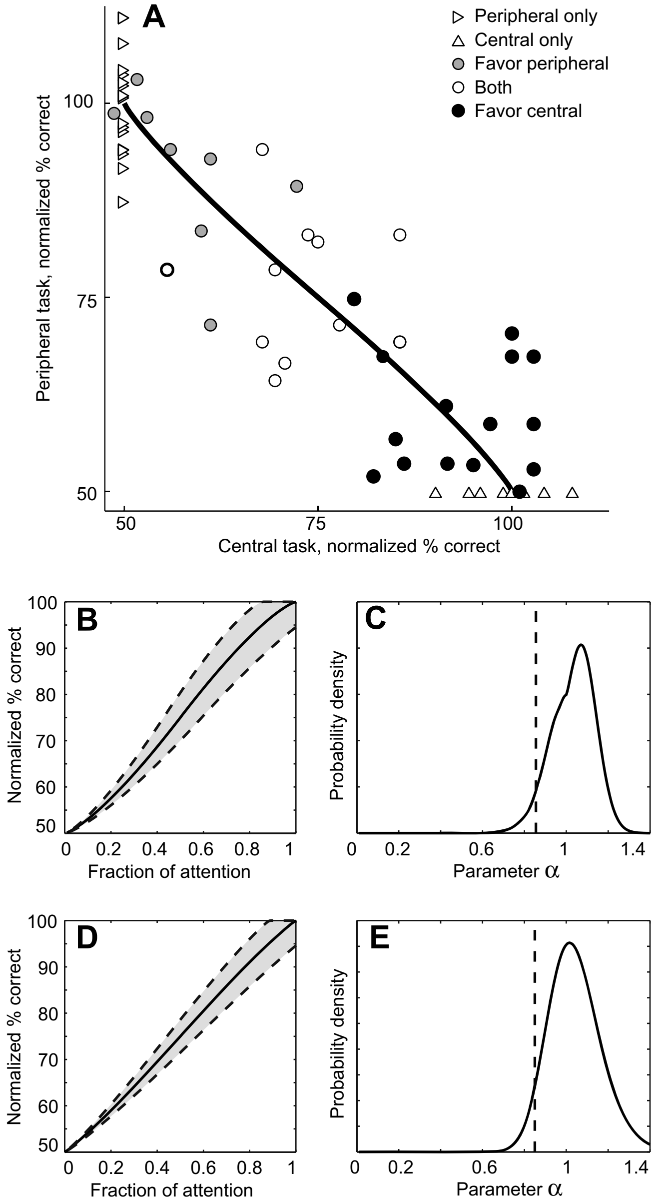

Fig. 3. Experiment 2: Color-position discrimination. (A) Results from 14 blocks central task only (single-task, triangles), 20 blocks peripheral task only (single-task, triangles), and 44 blocks of both tasks together (dual-task, circles). Shading of circles (white, gray, black) denotes different dual-task instructions (see Section 2). Dual-task results are fitted with an attention-operating characteristic (solid line). (B) Family of well-fitting performance-resource functions for central task ($p = .05$). (C) Likelihood distribution of parameter α_{central}. (D) Family of well-fitting performance-resource functions for peripheral task ($p = .05$). (E) Likelihood distribution of parameter $\alpha_{\text{peripheral}}$.

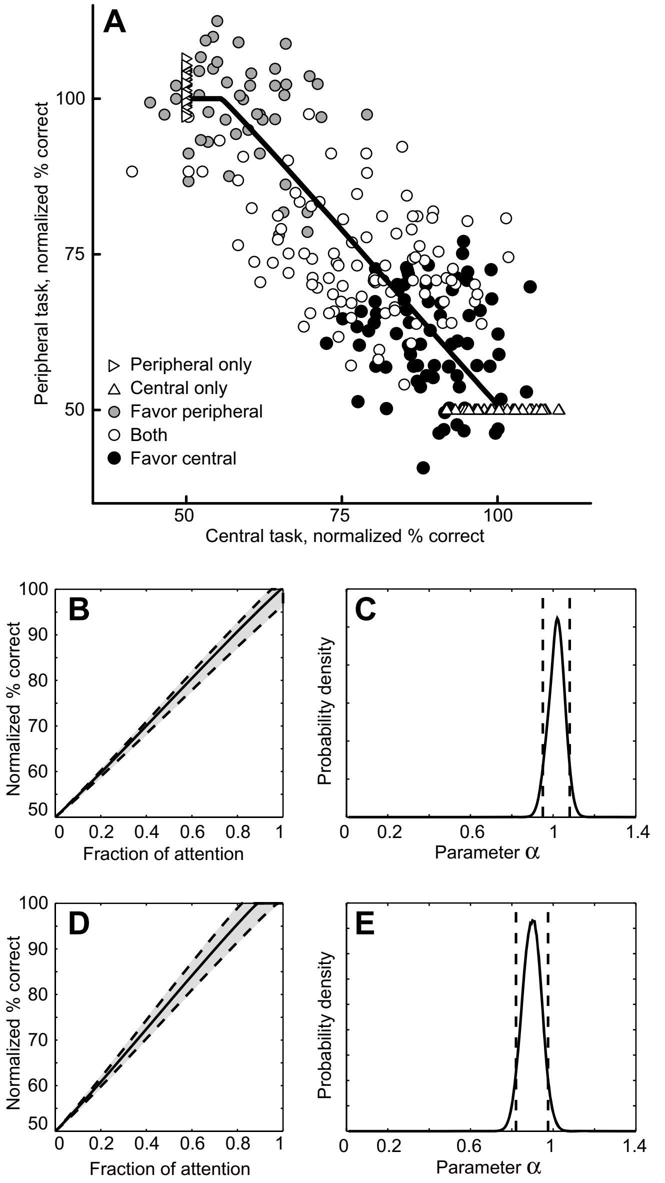

Fig. 4. Experiment 3: Rotating ellipse. (A) Results from 69 blocks central task only (single-task, triangles), 36 blocks peripheral task only (single-task, triangles), and 238 blocks of both tasks together (dual-task, circles). Shading of circles (white, gray, black) denotes different dual-task instructions (see Section 2). Dual-task results are fitted with an attention-operating characteristic (solid line). (B) Family of well-fitting performance-resource functions for central task ($p = .05$). (C) Likelihood distribution of parameter α_{central}. (D) Family of well-fitting performance-resource functions for peripheral task ($p = .05$). (E) Likelihood distribution of parameter $\alpha_{\text{peripheral}}$.

For this task combination, the trade-off between central and peripheral performance is almost symmetrical and task interference almost complete: when the central task is performed optimally, the peripheral task is performed at chance. Conversely, when the peripheral task is performed optimally, the central-task performance remains slightly better than chance. Qualitatively, this pattern of results suggests that central-task performance requires full attention and peripheral task performance almost full attention.

The quantitative analysis is shown in Fig. 4B–D. The fitted PRFs are almost linear and reach optimal performance only when attention is allocated fully, or almost fully to the task. The most likely attention demands are $\alpha = 102\%$ (range > 95%) for the central task and $\alpha = 90\%$ (range 82–98%) for the peripheral task. In spite of the different peripheral task, the central-task PRF remained essentially unchanged compared to Experiments 1 and 2. This is evident from Table 1, which compares the parameters of the central-task PRFs from Experiments 1–3. The comparatively high attention demand of the peripheral task confirms earlier results on the discrimination of rotational motion (Lee et al., 1999b).

3.4. Experiment 4: Moving plaid

The last experiment paired the central task with yet another peripheral task concerning visual motion. In contrast to the previous experiment, we wanted a small attention demand and

Table 1
The comparison of parameters of the central task between the experiments

	Experiment 1		Experiment 2		Experiment 3		Mean	
	α	β	α	β	α	β	α	β
Most likely value	99	1.11	107	1.27	102	1.13	102.7	1.17
95% range	>91.5	<1.83	>85.5	<2.54	>95	<1.65	>91	<2

Table 2
Observer average of the criterion-corrected performance (see Section 2) of the component tasks under single-task conditions

Experiment	Central in %	Peripheral in %
Color discrimination	77 ± 6	80 ± 11
Color position	75 ± 5	79 ± 6
Rotating ellipse	82 ± 4	93 ± 4
Moving plaid	80 ± 4	90 ± 3

therefore chose the discrimination of linear motion. The particular task used had been employed in a recent study (Pastukhov & Braun, 2007) and was replicated for the purposes of the present study. Other dual-task studies suggest that similar results can be obtained with other moving patterns (Tsuchiya & Braun, 2007). No masking was used and task difficulty was controlled by adjusting the speed of motion and the duration of the presentation.

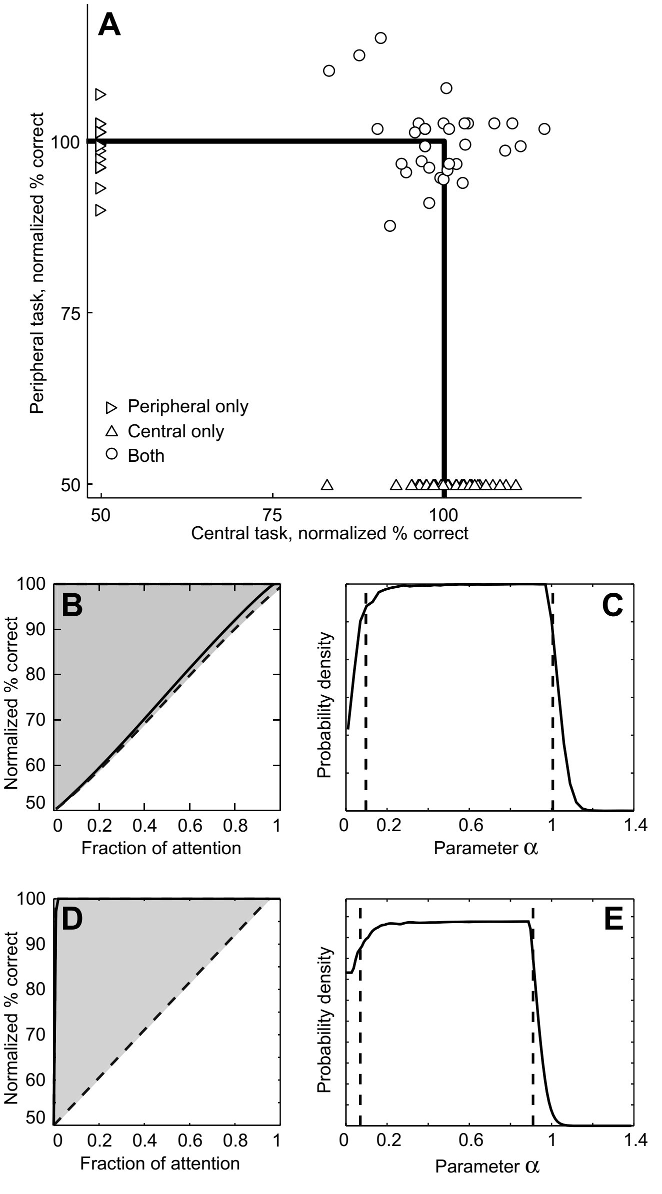

Fig. 5. Experiment 4: Moving plaid. (A) Results from 46 blocks central task only (single-task, triangles), 26 blocks peripheral task only (single-task, triangles), and 34 blocks of both tasks together (dual-task, circles). Shading of circles (white, gray, black) denotes different dual-task instructions (see Section 2). Dual-task results are fitted with an attention-operating characteristic (solid line). (B) Family of well-fitting performance-resource functions for central task ($p = .05$). (C) Likelihood distribution of parameter α_{central}. (D) Family of well-fitting performance-resource functions for peripheral task ($p = .05$). (E) Likelihood distribution of parameter $\alpha_{\text{peripheral}}$.

Four observers performed 72 *single-task* and 34 *dual-task* blocks. No significant (negative) correlations between central and peripheral task was observed ($\chi^2 = 3.12$, critical value for 95% confidence interval = 3.8). The combined results are shown in Fig. 5A.

For this task combination, there is little or no interference or trade-off between central and peripheral performance. Observers perform both tasks together comparably well as each task by itself. Qualitatively, this implies that at least one task (and possibly both tasks) poses little or no demand for attention. The quantitative analysis (Fig. 5), reflects the fundamental ambiguity of this outcome: the most likely attention demand of central and peripheral tasks are $\alpha = 95\%$ and $\alpha = 8.5\%$, respectively, but in both cases the confidence range is enormous.

By themselves, these results demonstrate merely that one cannot infer attention demand from task combinations that exhibit no interference and no performance trade-off. The comparison with Experiments 1–3 suggests a further and more interesting interpretation: assuming that the true attention demand of the central task lies near 100% (as measured consistently in Experiments 1–3), it follows that the attention demand of the peripheral task lies near 0%. In other words, the peripheral task in question is performed comparably well, whether attention is fully available (*single-task condition*) or whether attention is engaged by a demanding concurrent task (*dual-task condition*).

Table 2 reports the criterion-corrected performance (see Section 2) of all component tasks under single-task conditions. The roughly similar performance levels with attention fully available show that in each case the stimulus alternatives were comparably discriminable.

4. Discussion

Dual-task interference is typically observed when two tasks place particular demands on the same processing capacity. For example, two tasks that tax working memory, two tasks that demand speeded responses, or two tasks that require sensory selection in the same modality may be expected to interfere with each other. In general, therefore, dual-task interference arises from the fact that two tasks are similar in some way and draw on the same "specific resource" (Allport, 1980; Bourke, 1997; Navon, 1984). The "specific resource" investigated here was the limited capacity of visual selective attention. Accordingly, we combined tasks that required observers to select task-relevant from task-irrelevant visual attributes concurrently in two separate display regions. The demands on working memory were minimal (two binary choices) and responses were unspeeded.

We asked whether the "specific resource" of selective visual attention is differentiated or not. In particular, we wondered whether the principle of "similar tasks interfere, dissimilar ones don't" applies also to the specific visual attributes that are to be discriminated in each task: tasks involving the same visual attributes (e.g., luminance) interfere more than two tasks involving different visual attributes (e.g., luminance and color). Our results, however, suggested the opposite: when two concurrent tasks interfere at the level of visual selection, the degree of interference does not depend on the visual attributes concerned: selecting similar and dissimilar attributes produces the same interference. We conclude, therefore, that selective visual attention is a single, undifferentiated "specific resource".

Which visual attributes of a complex display can and cannot be discriminated concurrently and reported voluntarily reveals much about the nature of visual selection. Some of the most compelling evidence that attentional selection is based on "visual objects" defined by perceptual grouping derives from experiments with concurrent discriminations (e.g., Baylis & Driver, 1993; Blaser et al., 2000; Duncan, 1984; Luck & Vogel, 1997; Rodriguez, Valdes-Sosa, & Freiwald, 2002; Valdes-Sosa, Cobo, & Pinilla, 1998). From the attention-operating characteristic of a pair of visual discriminations, it can in many cases be determined how the response accuracy of each discrimination increases with allocation of attention, that is, the respective performance-resource functions can be established (e.g., Lee et al., 1999b; Sperling & Melchner, 1978). Such a detailed characterization of attentional demand is not available from any other source.

However, the interpretation of concurrent-discrimination experiments rests on an assumption that has been questioned repeatedly over the years (Allport, 1971; Morrone et al., 2002, 2004; Treisman, 1969). This is the assumption that all visual discriminations draw on the same attentional resource or, in other words, that visual attention is "undifferentiated" (Sperling & Dosher, 1986). This assumption is also central to the "integrated competition" hypothesis of Duncan and colleagues (Desimone & Duncan, 1995; Duncan, Humphreys, & Ward, 1997). In their view, visual objects compete for neural activity and "a gain in activity for one object is accompanied by a loss in activity for others". Although the response to each object includes activity in different neural "subsystems" representing different stimulus attributes (e.g., form, color, motion, etc.) the competition between objects is "integrated" across "subsystems": "as a winning object emerges in one subsystem, it tends also to become dominant in others" (Duncan et al., 1997, p. 255). Due to this interdependence of "subsystems", discriminating different attributes of different objects (e.g., motion and color, respectively) should be just a difficult as discriminating the same attributes (e.g., motion and motion). Thus, the "integrated competition" hypothesis implies that visual attention is "undifferentiated".

Some years ago, we tested the "undifferentiated" nature of visual attention by pairing visual discriminations of either color, motion, or form (Lee et al., 1999a, 1999b). We consistently obtained statistically indistinguishable performance-resource functions when we paired similar and dissimilar discriminations. This was true both for discriminations that reached optimal performance only with full attention ($\alpha \sim 1.0$) and for discriminations that were performed optimally already with partial attention ($\alpha \sim 0.75$). Accordingly, the results seemed the bear out the "undifferentiated" attention hypothesis. However, all of the discriminations used in these studies shared a spatial component: in each case, observers had to discriminate the precise relative position of items of different form, color, or motion. It could thus be argued that the discriminations in question all involved the same "subsystem" (relative position) and that this circumstance was responsible for the outcome.

The present study was conceived as a more stringent test of "undifferentiated" visual attention. One task (central tasks) involved discriminating the rotational motion of several centrally presented items and thus was expected to engage the hypothetical "subsystems" for motion and relative position. Other tasks (peripheral tasks 1 and 4) required the discrimination of color or motion attributes without a spatial component and were thus expected to engage "subsystems" for color or motion, respectively. Yet other tasks (peripheral tasks 2 and 3) combined the discrimination of color or motion with a discrimination of relative position. Thus, these tasks were expected to also engage a "subsystem" for relative position.

Accordingly, we were able to determine performance-resource functions from a task combination sharing no "subsystem" (Experiment 1), task combinations sharing one "subsystem" (relative position in Experiment 2, motion in Experiment 4), and a task combination sharing two "subsystems" (Experiment 3, motion and relative position).

The results were fully consistent with "undifferentiated" visual attention. The three task combinations posing a conflict (concurrent performance significantly below individual performance) yielded statistically indistinguishable performance-resource functions for the central task. In each combination, this task was performed optimally only with full attention (95% confidence ranges >91.5%, >85.5%, and > 95%). Thus, the measured demand for visual attention did not depend on how many hypothetical "subsystems" the central task shared with a concurrent peripheral task. We conclude that the observed performance-resource functions were characteristic for the central task (and not for the task combination). A fourth task combination posed no conflict (concurrent performance comparable to individual performance) and therefore did not restrict the range of possible performance-resource functions. This task combination confirmed that the investigated situation did not unduly tax limited resources other than visual attention, such as, for example, short-term memory or response preparation.

But what about the recent work reaching the opposite conclusion, namely, that discriminations of luminance and color contrast engage separate attentional resources (Morrone et al., 2002, 2004)? The studies in question combined a visual search task in the center of the display with a contrast discrimination task in the near periphery and compared performance of both tasks together with performance of either task alone. The peripheral task was performed better alone (discrimination thresholds were lower) than together with the central task, implying competition for attentional resources. Interestingly, the task conflict was observed only when both tasks involved the same type of contrast (either luminance or color contrast). When central and peripheral task concerned different contrast types, no conflict was obtained. Accordingly, these results appear consistent with separate attentional resources for luminance and color discrimination.

However, as pointed out elsewhere (Braun, 2002), the display layout of Morrone and colleagues also admits another interpretation based on grouping mechanisms. With the same contrast type in central and near peripheral parts of the display, the central task involved an attention-demanding discrimination of relative position, as the observer had to judge whether an odd contrast present was *also* in the search array or *only* in the immediately adjacent grating. With different contrast types, an odd contrast in the search array could not be confused with the adjacent grating, so that there was no need to discriminate relative position. As a result, the attentional demand of the central visual search may have been far higher in "same contrast" than in "different contrast" displays, which would also have accounted for the results. To decide between the original interpretation of Morrone and colleagues and the alternative offered here, the display layout would have to be modified to minimize perceptual grouping. In addition, it would be useful to confirm that the attentional demand of the central task was comparable in "same contrast" and "different contrast" displays.

We have shown here that a high attentional demand ($\alpha \sim 100\%$) remains constant in different task combinations, some involving entirely similar, others partially similar, and yet others entirely dissimilar visual attributes. This confirms and extends two earlier studies (Lee et al., 1999a, 1999b) of task combinations with entirely and partially similar visual attributes and, in one study, lower attentional demand ($\alpha \sim 75\%$). Clearly, it would be desirable to further extend the generality of these findings to tasks with even lower attentional demand ($\alpha \sim 30\%$, say). We have also confirmed that the discrimination of relative position (here: of moving items) places a particularly high demand on attention. We and others have extensively used "relative position" discriminations to infer the attention demand of other discriminations from the attention-operating characteristic of concurrent-task situations.

We conclude that selective visual attention operates as a single, undifferentiated resource in the visual tasks investigated here, as well as in other visual tasks investigated previously (Lee, Itti, et al., 1999). To confirm the generality of this conclusion, it will be necessary to conduct similar experiments with an even wider range of visual tasks, especially visual tasks that pose a smaller demand on selective visual attention. If confirmed, this would give us a reliable and consistent method for quantifying the demand for selective visual attention.

Once measurements of attention demand are generally accepted, a fundamental question will loom even larger than it does already: why should various visual discriminations pose such different demands on selective visual attention? For example, why should the discrimination of relative position require full attention, but many visual threshold judgments not (Lee, Itti, et al., 1999; Tsuchiya & Braun, 2007)? Why should the discrimination of perceptual organization demand full attention (Bauer & Braun, 2000), but not the classification of natural visual scenes (Li et al., 2002; Reddy et al., 2004, 2006). We cannot claim to have understood the way in which visual attention alters visual representations unless and until we can account for these dramatic variations in attentional demand.

References

Adelson, E. H., & Movshon, J. A. (1982). Phenomenal coherence of moving visual patterns. *Nature, 300*(5892), 523–525.

Allport, D. A. (1980). Attention and performance. In G. Claxton (Ed.), *Cognitive psychology: New directions* (pp. 112–153). London: Routledge & Kegan Paul.

Allport, D. A. (1971). Parallel encoding within and between elementary stimulus dimensions. *Perception & Psychophysics, 10*(2), 104–108.

Bauer, H. U., & Braun, J. (2000). Is there parallel binding of distributed objects? In H. Cruse, J. Dean, & H. Ritter (Eds.), *Preparational intelligence adaptive behavior and intelligent systems without symbols and logic 1* (pp. 163–174). Kluwer.

Baylis, G. C., & Driver, J. (1993). Visual attention and objects: Evidence for hierarchical coding of location. *Journal of Experimental Psychology: Human Perception and Performance, 19*(3), 451–470.

Blaser, E., Pylyshyn, Z. W., & Holcombe, A. O. (2000). Tracking an object through feature space. *Nature, 408*(6809), 196–199.

Bonnel, A. M., & Prinzmetal, W. (1998). Dividing attention between the color and the shape of objects. *Perception & Psychophysics, 60*(1), 113–124.

Bourke, P. A. (1997). Measuring attentional demand in continuous dual-task performance. *The Quarterly Journal of Experimental Psychology A, 50*(4), 821–840.

Braun, J. (1994). Visual search among items of different salience: Removal of visual attention mimics a lesion in extrastriate area V4. *The Journal of Neuroscience, 14*(2), 554–567.

Braun, J. (1998). Divided attention: Narrowing the gap between brain and behavior. In R. Parasuraman (Ed.), *The attentive brain* (pp. 327–351). Cambridge, MA: MIT Press.

Braun, J. (2002). Visual attention: Light enters the jungle. *Current Biology, 12*(17), R599–R601.

Braun, J. (2008). *Attention and awareness. Oxford encyclopedia of consciousness*. Oxford: OUP.

Braun, J., & Julesz, B. (1998). Withdrawing attention at little or no cost: Detection and discrimination tasks. *Perception & Psychophysics, 60*(1), 1–23.

Braun, J., & Sagi, D. (1991). Texture-based tasks are little affected by second tasks requiring peripheral or central attentive fixation. *Perception, 20*(4), 483–500.

Braun, J., Koch, C., Lee, D. K., & Itti, L. (2001). Perceptual consequences of multilevel selection. In J. Braun, C. Koch, & J. Davis (Eds.), *Visual attention and cortical circuits* (pp. 215–242). Cambridge, MA: MIT Press.

Dehaene, S., Changeux, J. P., Naccache, L., Sackur, J., & Sergent, C. (2006). Conscious, preconscious, and subliminal processing: A testable taxonomy. *Trends in Cognitive Sciences, 10*(5), 204–211.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience, 18*, 193–222.

Driver, J., & Frith, C. (2000). Shifting baselines in attention research. *Nature Reviews Neuroscience, 1*(2), 147–148.

Duncan, J. (1984). Selective attention and the organization of visual information. *Journal of Experimental Psychology: General, 113*(4), 501–517.

Duncan, J. (1993). Similarity between concurrent visual discriminations: Dimensions and objects. *Perception & Psychophysics, 54*(4), 425–430.

Duncan, J. (1996). Cooperating brain systems in selective perception and action. *Attention and performance* (XVI, pp. 549–578). Cambridge, MA: MIT Press.

Duncan, J., & Nimmo-Smith, I. (1996). Objects and attributes in divided attention: Surface and boundary systems. *Perception & Psychophysics, 58*(7), 1076–1084.

Duncan, J., Humphreys, G., & Ward, R. (1997). Competitive brain activity in visual attention. *Current Opinion in Neurobiology, 7*(2), 255–261.

Joseph, J. S., Chun, M. M., & Nakayama, K. (1997). Attentional requirements in a preattentive feature search task. *Nature, 387*(6635), 805–807.

Kommerell, G., & Thiele, H. (1970). Der optokinetische Kurzreiznystagmus [Optokinetic short-stimulation nystagmus]. *Albrecht von Graefes Archiv fur Klinische und Experimentelle Ophthalmologie, 179*(3), 220–234.

Lee, D., Koch, C., & Braun, J. (1999a). Visual attention is undifferentiated also for less demanding tasks. *Investigative Ophthalmology & Visual Science (Suppl.), 40*, S52.

Lee, D. K., Itti, L., Koch, C., & Braun, J. (1999). Attention activates winner-take-all competition among visual filters. *Nature Neuroscience, 2*(4), 375–381.

Lee, D. K., Koch, C., & Braun, J. (1999b). Attentional capacity is undifferentiated: Concurrent discrimination of form, color, and motion. *Perception & Psychophysics, 61*(7), 1241–1255.

Li, F. F., VanRullen, R., Koch, C., & Perona, P. (2002). Rapid natural scene categorization in the near absence of attention. *Proceedings of the National Academy of Sciences of the United States of America, 99*(14), 9596–9601.

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature, 390*(6657), 279–281.

Morrone, M. C., Denti, V., & Spinelli, D. (2002). Color and luminance contrasts attract independent attention. *Current Biology, 12*(13), 1134–1137.

Morrone, M. C., Denti, V., & Spinelli, D. (2004). Different attentional resources modulate the gain mechanisms for color and luminance contrast. *Vision Research, 44*(12), 1389–1401.

Navon, D. (1984). Resourcesâ—A theoretical soup stone? *Psychological Review, 91*(2), 216–234.

Norman, D. A., & Bobrow, D. G. (1975). On data-limited and resource-limited processes. *Cognitive Psychology, 7*(1), 44–64.

O'Regan, J. K., & Noe, A. (2001). A sensorimotor account of vision and visual consciousness. *The Behavioral and Brain Sciences, 24*(5), 939–973. discussion 973–1031.

Pashler, H. E. (1999). *The psychology of attention* (Vol. 510). MIT Press.

Pastukhov, A., & Braun, J. (2007). Perceptual reversals need no prompting by Attention. *Journal of Vision, 7*(10), 1–17.

Pastukhov, A., Festman, Y., Braun, J. (2004). A new window on biased competition: Attention and coherent pattern motion [Abstract]. *Journal of Vision, 4*(8), 849, 849a. Available from http://journalofvision.org/4/8/849/.

Pola, J., Wyatt, H. J., & Lustgarten, M. (1995). Visual fixation of a target and suppression of optokinetic nystagmus: Effects of varying target feedback. *Vision Research, 35*(8), 1079–1087.

Posner, M. I. (1994). Attention: The mechanisms of consciousness. *Proceedings of the National Academy of Sciences of the United States of America, 91*(16), 7398–7403.

Reddy, L., Reddy, L., & Koch, C. (2006). Face identification in the near-absence of focal attention. *Vision Research, 46*(15), 2336–2343.

Reddy, L., Wilken, P., & Koch, C. (2004). Face-gender discrimination is possible in the near-absence of attention. *Journal of Vision, 4*(2), 106–117.

Reynolds, J. H., & Chelazzi, L. (2004). Attentional modulation of visual processing. *Annual Review of Neuroscience, 27*, 611–647.

Rodriguez, V., Valdes-Sosa, M., & Freiwald, W. (2002). Dividing attention between form and motion during transparent surface perception. *Brain Research: Cognitive Brain Research, 13*(2), 187–193.

Roelfsema, P. R., Lamme, V. A., & Spekreijse, H. (1998). Object-based attention in the primary visual cortex of the macaque monkey. *Nature, 395*(6700), 376–381.

Saenz, M., Buracas, G. T., & Boynton, G. M. (2003). Global feature-based attention for motion and color. *Vision Research, 43*(6), 629–637.

Scholl, B. J. (2001). Objects and attention: The state of the art. *Cognition, 80*(1–2), 1–46.

Sperling, G., & Dosher, B. A. (1986). Strategy and optimization in human information processing. In L. K. K. Boff & J. Thomas (Eds.). *Handbook of perception and human performance* (Vol. 1, pp. 2-1–2-65). New York: Wiley.

Sperling, G., & Melchner, M. J. (1978). The attention operating characteristic: Examples from visual search. *Science, 202*(4365), 315–318.

Treisman, A. (1969). Strategies and models of selective attention. *Psychological Review, 76*, 282–299.

Treisman, A. M., & Kanwisher, N. G. (1998). Perceiving visually presented objects: Recognition, awareness, and modularity. *Current Opinion in Neurobiology, 8*(2), 218–226.

Tsuchiya, N., & Braun, J. (2007). Contrast thresholds for component motion with full and poor attention. *Journal of Vision, 7*(3), 1–15.

Tyler, C. W. (1997). Colour bit-stealing to enhance the luminance resolution of digital displays on a single pixel basis. *Spatial Vision, 10*(4), 369–377.

Valdes-Sosa, M., Cobo, A., & Pinilla, T. (1998). Transparent motion and object-based attention. *Cognition, 66*(2), B13–B23.

VanRullen, R., Reddy, L., & Koch, C. (2004). Visual search and dual tasks reveal two distinct attentional resources. *Journal of Cognitive Neuroscience, 16*(1), 4–14.

Ward, R., Duncan, J., & Shapiro, K. (1997). Effects of similarity, difficulty, and nontarget presentation on the time course of visual attention. *Perception & Psychophysics, 59*(4), 593–600.