Interactions between task difficulty and hemispheric distribution of attended locations: implications for the splitting attention debate

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Abstract

Whether attention can be split between multiple regions in space simultaneously is an ongoing controversy in attention research. We argue that the debate could be resolved if the distribution of target locations over hemifields and task difficulty are both considered. This premise was tested in five experiments in which 48 subjects compared the identity of two out of four stimuli. In an easy task, within each hemifield, performance (reaction times and error rates) was better for adjacent targets than for separated ones, but across hemifields, performance for separated and adjacent stimuli was similar. In difficult tasks, performance was always better when the stimuli were presented across the hemifields indicating a bilateral field advantage. Moreover, the difference between adjacent and separate conditions within one hemifield diminished with increasing task difficulty. We propose a modified model of visuo-spatial attention, which permits the hemispheres to maintain and control simultaneous attentional foci.

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1. Introduction

In natural visual scenes, behaviorally relevant stimuli can either be arranged in adjacent locations or can be spread over the entire visual field, with irrelevant positions and distractors between them. A controversy in the attention research literature addresses the question whether spatial attention can be split between locations without filling the space in between. In recent years two contrary views have been proposed. Some authors favor the idea of a unitary focus of attention (the “unitary view”) (e.g., [18,39]). They claim that in order to attend two separated locations simultaneously, the focus of attention has to be adjusted in size like a zoom lens (e.g., [14]). Hence, when both locations are encompassed by that focus, so are the irrelevant locations between them. Consequently, distractors at intervening locations can interfere with the processing of relevant information. Moreover, the increased size of the attentional focus can strain the limited attentional resources (e.g., [35]). Reaction times and accuracy rates should therefore be worse when attending separated as compared to adjacent locations in space. In contrast to this view, other authors (e.g., [2,47]) have argued that attention can be allocated to noncontiguous positions (the “split-attention view”). These authors predict comparable performance...
when subjects have to attend two different locations in space simultaneously, whether they are adjacent or separated. By now, multiple studies using a variety of covert attention paradigms have provided evidence for both theories (e.g., [2,4,7,18,23,31,32]). It remains to be resolved what factors led to the evidence favoring each of the competing views.

Our review of the literature suggested two major factors may be relevant to the contradictory findings. First, task difficulty seems to have a major influence on visuo-spatial selective attention [24]. Second, studies on eye movements (e.g., [9,46]), split-brain patients (e.g., [1,29]), and the bilateral field advantage (e.g., [6,46]) suggest that the ability to split attention might depend on the distribution of attended locations over hemifields[7]. These factors are considered in greater detail below.

1.1. Influence of task difficulty on visuo-spatial attention

In 1995, Lavie [24] tried to resolve the early–late selection debate ([5] vs. [11]) in visual processing by suggesting a hybrid resource model of visuo-spatial attention. She postulated that the exclusion of irrelevant distracter stimuli at early or late processing stages depends on the task load. “Irrelevant information is processed as long as it falls within the capacity limits (late selection), but it fails to be processed as soon as it exceeds the limit (early selection)” [25]. In several psychophysical experiments, she found evidence for less interference from irrelevant distracters when task difficulty increased [24].

This notion may explain why studies which used a small number of simple distracter stimuli and easy to distinguish target stimuli (e.g., [18]) found evidence for the “unitary view”, while studies which used more complex paradigms (e.g., conjunction-based stimuli, large numbers of distracters) supported the “split view” of attention (e.g., [2]). The model of Lavie suggests that complex paradigms lead to the earlier exclusion of irrelevant distracter stimuli information. In this case, the use of complex stimuli would lead to comparable performance for adjacent and separated attended locations, because intervening distracter information would not be processed beyond an early stage. Such an observation could then be interpreted as an indication of separate attentional foctions. In contrast, in easy tasks, attentional resources are sufficient to process irrelevant distracter information, resulting in an apparent unitary focus of attention. We will refer to this hypothesis as the “task difficulty hypothesis”.

1.2. The distribution of attended locations over the visual hemifields

Most studies on splitting attention (e.g., [18,36]) have positioned targets in the upper visual field, with two positions in the left hemifield and two in the right hemifield. As a result, separated locations were on opposing sides of the vertical meridian and adjacent locations within a single hemifield. From earlier studies, it is known that the allocation of attention across the vertical meridian differs from the allocation within one hemifield. On the one hand, studies (e.g., [20,42]) where spatial attention had to be redirected from one specific location to another revealed additional costs when the task requires attentional shifts across the vertical meridian compared to shifts within one hemifield. On the other hand, studies where two items must be compared have reported a bilateral field advantage (e.g., [3,6,46]). For instance, Sereno and Kosslyn [46] presented two groups of characters within one hemifield or across hemifields without a distracter between them. Discrimination performance was faster when stimuli were presented in different hemifields than in the same one. This bilateral field advantage was stable in both easy (single feature) tasks and more demanding (conjunction-based) discrimination tasks. By contrast, Banich (e.g., [3]) mainly found a bilateral field advantage in difficult tasks whereas a unilateral field advantage was observed in easy tasks.

In consequence, most studies concerned with spatially divided attention have confounded attention to non-adjacent locations with bilateral stimulus presentations. One exception is the study of Awh and Pashler [2]. They compared detection performances when two separated locations were vertically aligned in one hemifield or horizontally aligned across hemifields. An advantage was found when locations were aligned horizontally, supporting the idea of a bilateral field advantage. These outcomes suggest that it may be easier to split attention between the hemifields than within one hemifield. This view will be referred to as the hemifield hypothesis.

The aim of the study was to resolve the conflicting views on spatially divided attention using psychophysical measures by systematically manipulating both task difficulty and the spatial distribution of attended locations. It was hypothesized that the ability to split attention depends on interplay of these factors. Similar designs were used in five experiments (Exp.), with systematic variations of relevant factors (target locations and task difficulty). The hemifield hypothesis was tested by placing both adjacent and separated target locations within and across hemifields (Exp.1). In two experiments (Exp.2A and B), the influence of task difficulty on subjects’ ability to attend to separated locations was addressed. In two additional experiments (Exp.3A and B), the effect of positioning stimuli in the upper, lower, right, and left visual fields was evaluated. Note that, neither models of a unitary focus of attention nor models suggesting multiple foci of attention take these

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2 Each meridian (vertical/horizontal) divides the whole visual field into two hemifields (left/right vs. upper/lower hemifield). In the following, when the term hemifield is used, it refers to the distinction between the left and right hemifields.
aspects into consideration. The implications of a modified model of attention with specific neuroanatomical constraints, as well as the validity of current models, will be discussed.

2. Materials and methods

2.1. Subjects

Forty-eight healthy right-handed students with normal vision (mean age 22.8 years, SD = 3.32) from the Humboldt University of Berlin participated in two 120-min sessions, one on each of two successive days. Informed consent was obtained from each participant and they were paid for their participation or received course credits. Each subject performed two experiments—Exp.1 and either Exp.2A, 2B, 3A, or 3B. Half of them started with Exp.1, the others performed one of Exp.2A/B, 3A/B first. Different experimental orders were randomly assigned to participants in order to avoid practice effects as a potential confounder. All subjects were unaware of the purpose of the experiments. Three subjects were excluded for exceeding a 20% error rate or of failure to maintain central fixation in more than 20% of the trials.

2.2. Infrared-oculography

To ensure subjects maintained proper fixation, eye movements were recorded with the I-View-System of SMI (Sensomotoric Instruments, Berlin-Teltow) using the I-View 3.01.11 software. Subjects had to maintain fixation during the cueing phase within 2° of the fixation cross.

2.3. Apparatus and stimuli

Stimuli were presented on a 17-in. PC monitor. Observers were seated 112 cm from the display. The head was stabilized by a chin rest in order to minimize head movements and to ensure a fixed viewing distance. The software program ERTS (Experimental Run Time System, BeriSoft Cooperation, Frankfurt) was used to present stimulus displays and collect performance data. Fig. 1 (left) illustrates the experimental design.

A central fixation cross (1° × 1°, black) and four squares indicating the stimulus positions (1.4° × 1.4°, black) were presented on a gray background (1 cd/m²). Four different central cues (1° × 1°, white) marked the relevant stimulus positions in the various conditions. In each experiment, three 1.1° × 1.1° stimuli were used as targets (see Fig. 1, right). The form and the colors of the targets were varied across the experiments, described in the next section.

2.4. Task difficulty manipulations

Several previous studies investigated task difficulty dependencies. This has been done by manipulating the number of distracters [2,24] or feature-based versus conjunction-based stimuli [24]. In our experiments, we investigated the role of task difficulty while holding stimulus locations constant. In Exp.1, 3A, and 3B, three easily distinguishable objects were used (circle, square, and...
triangle 1.1° × 1.1°, black, see Fig. 1, right). In Exp.2A, task difficulty was increased by replacing the stimuli of Exp.1 with three symbols (1.1° × 1.1°, black). This manipulation of task difficulty was adopted from the work of Duncan and Humphreys [13]. While Exp.1 allowed feature-based discrimination, Exp.2A required a conjunction of two differently oriented bars, which is known to be more demanding [49]. The aim of Exp.2B was to replicate the results of Exp.2A using a different type of difficulty manipulation, so as to verify the generality of the observed effect of task difficulty. We wished to do this in a way that would not potentially confound difficulty with reported differences between the processing of feature-based and conjunction-based stimuli [12,49]. For this reason, we decided to increase task difficulty by reducing the contrast of the stimuli used in Exp.1.

2.5. Experimental design

The fixation cross and the four squares were presented throughout the entire experiment. The squares allowed subjects to more precisely direct voluntary attentional shifts [50]. The squares were arranged on an imaginary straight line rather than a circle (inner positions 3.4°, outer positions 6.1°, see Fig. 2, left). This alignment ensured that in the separated-stimuli conditions, the distracter stimulus was positioned exactly between the relevant stimulus locations. Distance between adjacent positions was 1.7°, distance between separated positions was 5.1°.

The cues and the fixation cross were presented in the center of the display. In each condition, subjects were instructed to attend one outer and one inner position. This permitted a comparison between adjacent (ADJ) and separated (SEP) positions in one hemifield (1 HEM) and both hemifields (2 HEM) with no difference in overall eccentricity between conditions (see Fig. 2, left). In Exp.1 and Exp.2, Position 1 was located 1.2° above the horizontal meridian and 6° left of the vertical meridian, Position 2 was located 1.2° below the horizontal and 3.6° left of the vertical meridian, Position 3 was aligned 3.6° below the horizontal and 1.2° left of the vertical meridian, and Position 4 was located 6° below the horizontal and 1.2° right of the vertical meridian. The eccentricities and stimulus timing were chosen to be compatible to the technical demands of a later functional imaging study.

2.6. Visual field alignment

In Exp.1 and 2, stimulus locations were presented on both sides of the horizontal meridian, but were mainly in the lower left visual field (see Fig. 2, left). Previous studies have documented not only left vs. right hemifield differences (e.g., [27,30]), but also differences between the upper and lower visual fields (e.g., [21,28,38]). To show our observed

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Fig. 2. Left: Four conditions were used. The circles indicate the cued locations. Relevant locations could either be adjacent (ADJ) or separated (SEP) by an intervening distracter and were located in one (1 HEM) or across hemifields (2 HEM). Right: Arrangement of the stimulus locations in Experiments 1 and 2 (left condition), Experiment 3A (right condition), and Experiment 3B (upper condition).
results were general for the right, left, upper, and lower visual fields, we ran two experiments (Exp.3A and 3B) in which stimulus locations were manipulated systematically with respect to the retinal meridians (see Fig. 2, right). In Exp.3A, the alignment of stimulus locations was mirrored horizontally. In Exp.3B, stimulus locations were mirrored vertically; Position 1 was now aligned 1.2° below the horizontal meridian while Position 4 was presented 6° above the horizontal meridian.

2.7. Procedure

The subjects’ task was to compare the identity of two out of four stimuli. Relevant locations were either adjacent or separated by an intervening distracter and were located in the same or in opposing hemifields, resulting in four experimental conditions (see Fig. 2, left). Subjects were instructed to perform the discrimination task by shifting attention to the relevant positions while maintaining central fixation. Each trial started with an initial fixation period of 3 s, during which the fixation cross and the four frames were presented on the screen (Fig. 1, left). The two relevant locations were indicated by central cues several seconds (4 s, 7 s, 10 s in a randomized order) before the onset of the stimuli. The variable delay served to prevent anticipatory responses. The four cue arrangements are depicted in Fig. 1, left. Each of the cue conditions appeared equally often in a randomized order. By maintaining the cue, potential working memory effects were minimized [17]. The actual stimulus array was presented for 100 ms. Subjects had to respond with a same/different judgment within 1.5 s by pressing buttons with their right index or right middle finger (randomized across subjects). The stimuli matched in half of the trials.

In each of the two experimental sessions, subjects completed two blocks of 192 trials. The sessions started with a practice block, which ended when an accuracy rate of 80% was reached. After calibration of the eye tracking system, the first block started with 4 practice trials, followed by 96 experimental trials (24 trials per condition). A pause of 10 min was provided after the first block. The eye tracking system was recalibrated prior to the second experimental block, which started with 4 practice trials.

2.8. Data analysis

Statistical data analyses were conducted with the SPSS software (Version 10.0). Responses were excluded from analysis when RTs were shorter than 150 ms or longer than 1500 ms, when responses were incorrect, when eye movements were detected during the cueing phase (>2° from fixation) or when RTs differed more than ±2 standard deviations from the mean of the sample distribution of each experimental condition. On the average, 16% of the trials were excluded. Mean RTs and error rates were entered in two- and three-way repeated measures ANOVAs (all Experiments: factors “hemifield” and “position”; Exp.2A/B additional factor “task difficulty”, Exp.3A/B third factor “location”). In all experiments, Bonferroni-corrected pairwise comparisons were then used to evaluate the differences between specific condition means.

3. Results

3.1. Hemifield hypothesis—Experiment 1

In Exp.1, the hemifield hypothesis was tested using an easy feature-based discrimination task. We tested if the hemifield distribution of separated stimulus locations either within one hemifield or across two hemifields determines whether the attentional focus can be split or not. We reasoned that the hemifield hypothesis would predict that within one hemifield attending two separated locations would lead to reduced discrimination performance compared to adjacent locations. In contrast, adjacent and separated stimuli aligned across hemifields should be discriminated equally well. Mean reaction times (RTs) and error rates (N = 45 subjects) were entered in two-way repeated measures ANOVAs with the factors “hemifield” (1 HEM vs. 2 HEM) and “position” (ADJ vs. SEP). Mean RTs for each condition are shown in Fig. 3A. There was a significant main effect for both hemifield, F(1,44) = 13.57, P = 0.001, and position, F(1,44) = 43.8, P < 0.001, and a significant interaction between these factors, F(1,44) = 15.92, P < 0.001.

When attended stimuli were located in one hemifield, RTs for adjacent stimuli (ADJ-1 HEM M = 805 ms) were faster than for separated ones (SEP-1 HEM M = 875 ms) (P < 0.001). There was also a significant but smaller difference between the adjacent (ADJ-2 HEM M = 796 ms) and separated (SEP-2 HEM M = 828 ms) conditions across hemifields (P = 0.001). Thus, there was always a difference in RTs between attending two separated versus two adjacent locations (1 HEM = 70 ms vs. 2 HEM = 32 ms), but this difference was significantly reduced (47 ms) when stimuli were aligned across hemifields (P < 0.001). In contrast, with adjacent stimuli, the between-field RT was only 9 ms faster than the within-field RTs. This difference was not significant. Hence, no bilateral field advantage was found for adjacent conditions.

The mean error rates within each condition are presented in Fig. 3B. With separated stimuli, there was a clear increase in error rates when stimuli were located in the same hemifield compared to when they were in the opposing hemifields (M = 19.6% vs. 9.5%). No comparable increase was observed for adjacent stimuli (ADJ-1 HEM M = 7.7% vs. ADJ-2 HEM M = 8.3%). The reliability of this difference was confirmed by a two-way analysis of variance (ANOVA). Significant main effects for hemifield, F(1,44) = 19.12, P < 0.001, and position, F(1,44) = 19.12, P < 0.001, were obtained, but again, there was a significant interaction
between hemifield and position, $F(1,44) = 29.9, P < 0.001$. Note that the error rates for separated locations across hemifields are comparable to those for adjacent positions.

3.2. Task difficulty hypothesis—Experiment 2A and B

3.2.1. Feature- vs. conjunction-based discrimination—Experiment 2A

Based on the task difficulty hypothesis, we predicted that with increased task difficulty, the influence of distracter stimuli would be reduced, so that the adjacent and separated stimulus conditions would become more similar. To compare performance in the easy feature-based discrimination task used in Exp.1 and the difficult conjunction task used in Exp.2A, mean RTs and error rates from the 11 subjects who participated in both experiments (order of experiments balanced across subjects) were analyzed in three-way repeated measures ANOVAs with the factors “hemifield” (1 HEM vs. 2 HEM), “position” (ADJ vs. SEP), and “task difficulty” (feature vs. conjunction). The mean RTs of Exp. 2A are presented in Fig. 4A. A three-way ANOVA shows a significant main effect of task difficulty, $F(1,10) = 4.99, P = 0.049$, confirming that task difficulty was effectively manipulated by the change in the target stimuli.

In the difficult task, subjects responded slower in all conditions than they did in the easy task (ADJ-1 HEM 946 vs. 820 ms, ADJ-2 HEM 884 vs. 786 ms, SEP-1 HEM 987 vs. 901 ms, SEP-2 HEM 924 vs. 825 ms). In addition, significant main effects were obtained for the factors hemifield, $F(1,10) = 16.51, P = 0.002$, and position, $F(1,10) = 17.43, P = 0.002$. Moreover, there is a significant three-way interaction between the factors hemifield, position, and task difficulty, $F(1,10) = 4.94, P = 0.050$. This three-way interaction indicates that the differences between the adjacent and separated conditions due to the hemifield placement of the stimuli are not independent of task difficulty. In the easy task, a two-hemifield advantage occurred only for the separated conditions, while in the difficult task performance was better in both (adjacent and separated) conditions when stimuli were presented across the hemifields. Pairwise comparisons between the adjacent and separated conditions within one hemifield showed that the difference between those two conditions diminished with increasing task difficulty (820 ms vs. 901 ms in the easy task; 946 ms vs. 987 ms in the difficult task) and reached significance only under low task difficulty (easy task $P = 0.004$ vs. difficult task $P > 0.05$). Moreover, the slight increase in RTs when attending two separated

Fig. 4. Exp.2A—Difficult conjunction-based discrimination task ($N = 11$): mean RTs (A) and mean error rates (B) at adjacent and separated locations as a function of hemifield location (1 HEM vs. 2 HEM) when three symbols were used as stimuli.
locations across hemifields failed to reach significance with higher task demands (ADJ-2 HEM vs. SEP-2 HEM: easy task \( P = 0.034 \) vs. difficult task \( P > 0.05 \)). Note that one must act with caution in comparing these results with results from Exp.1 (whole group). Differential number of samples \((N = 11 \text{ vs. } N = 45)\) confound a direct comparison.

Task difficulty had a strong effect on the accuracy rates. The mean error rates of Exp.2A are presented in Fig. 4B. A three-way ANOVA showed a main effect of task difficulty on the number of errors, \( F(1,10) = 21.56, F(1,10) = 0.001 \). Overall, performance was lower in Exp.2A (19.6% errors) than in Exp.1 (9.8% errors). Thus, task difficulty was successfully manipulated. The significant main effects for the factors hemifield, \( F(1,10) = 12.22, F(1,10) = 0.006 \), and position, \( F(1,10) = 5.74, P = 0.038 \), as well as the interaction between hemifield and position, \( F(1,10) = 8.85, P = 0.014 \), were replicated. In addition, the factors task difficulty and hemifield interacted significantly, \( F(1,10) = 11.17, P = 0.007 \), reflecting that the bilateral field advantage is pronounced in the difficult task. As can be seen in Fig. 4B, with high task demands, error rates were higher when stimuli were presented within one visual field, relative to the rates with bilateral presentations (ADJ-1 HEM \( M = 22.6\% \), ADJ-2 HEM \( M = 12.8\% \), SEP-1 HEM \( M = 30.1\% \), SEP-2 HEM \( M = 12.9\% \)). This was the case in both the adjacent and separated conditions. However, under low task demands, error rates in the separated conditions were only higher with unilateral presentations (ADJ-1 HEM \( M = 7.8\% \), ADJ-2 HEM \( M = 7.6\% \), SEP-1 HEM \( M = 15.9\% \), SEP-2 HEM \( M = 7.8\% \)). Pairwise comparisons confirm that in the easy task accuracy rates for the adjacent positions did not differ within and across hemifields \((P > 0.05)\), but differed significantly when the task was demanding \((P = 0.016)\).

3.2.2. Easy vs. hard detectable stimuli—Experiment 2B

The aim of Exp.2B was to replicate the results of Exp.2A using a different type of difficulty manipulation. To allow a direct comparison of the discrimination performance when attending easily detectable stimuli used in Exp.1 and hard-to-detect stimuli used here, mean RTs and error rates from the 12 subjects who participated in both experiments (order randomized across subjects) were analyzed with three-way repeated measures ANOVAs, with factors “hemifield” (1 HEM vs. 2 HEM), “position” (ADJ vs. SEP positions), and “task difficulty” (high vs. low contrast). The mean RTs of Exp.2B are depicted in Fig. 5A. In Exp.2B, subjects responded slower in all conditions than in the easy task (ADJ-1 HEM 852 vs. 803 ms, ADJ-2 HEM 839 vs. 789 ms, SEP-1 HEM 890 vs. 866 ms, SEP-2 HEM 840 vs. 814 ms). However, a three-way ANOVA showed no significant main effect for task difficulty, \( F(1,11) = 1.77, P > 0.05 \).

The main effects for the factors hemifield, \( F(1,11) = 5.95, P = 0.033 \), position, \( F(1,11) = 10.17, P = 0.009 \), and the interaction between the factors hemifield and position, \( F(1,11) = 8.54, P = 0.014 \), were once more significant. RTs for both the low and high contrast tasks were slowest when separated stimuli had to be attended within one hemifield.

In contrast to the RT data, the manipulation of task difficulty by reduction in stimulus contrast can be confirmed statistically with error rates. A three-way ANOVA was also used to analyze error rates. There was a significant main effect for the factor task difficulty, \( F(1,11) = 13.06, P = 0.004 \). Fig. 5B illustrates the overall increase in error rates for the demanding low contrast conditions (Exp.2B) compared to the high contrast conditions (ADJ-1 HEM 16.5 vs. 6.9%, ADJ-2 HEM 12.1 vs. 8.7%, SEP-1 HEM 19.3 vs. 18%, SEP-2 HEM 10.9 vs. 10%). The mean number of errors was 14.5% in the low contrast task (Exp.2B) and 10.9% in the high contrast task (Exp.1). The ANOVA also revealed significant main effects for the factors hemifield, \( F(1,11) = 11.77 P = 0.006 \), and position, \( F(1,11) = 6.95, P = 0.023 \). The interaction between the factors hemifield and position, \( F(1,11) = 4.7, P = 0.053 \), was marginal and not significant. As in Exp.2A, the factors task difficulty and hemifield interacted significantly, \( F(1,11) = 7.42, P = 0.020 \), indicating a stronger bilateral field advantage with high task demands. Furthermore, as in Exp.2A, the difference between the adjacent and separated conditions within one hemifield was reduced with increasing task demands.

![Fig. 5. Exp.2B—Difficult feature-based discrimination task (N = 12): mean RTs (A) and mean error rates (B) at adjacent and separated locations as a function of hemifield location (1 HEM vs. 2 HEM) when hard detectable feature stimuli were used as stimuli.](image-url)
3.3. Visual field differences—Experiment 3A and B

3.3.1. Left vs. right visual field—Experiment 3A

Exp.3A was designed to determine whether the same results for two separated locations within and across hemifields can be observed when stimulus locations were presented in the right lower visual field (see Fig. 2, right). Mean RTs and error rates of the subgroup (N = 11) participated in Exp.3A and Exp.1 (order balanced across subjects) were entered in three-way repeated measures ANOVAs with factors “hemifield” (1 HEM vs. 2 HEM), “position” (ADJ vs. SEP), and “location” (left vs. right field). Mean RTs for right hemifield conditions (Exp.3A) are presented in Fig. 6A.

A three-way ANOVA revealed significant effects for the factors hemifield, $F(1,10) = 66.67$, $P = 0.027$, and position, $F(1,10) = 29.75$, $P < 0.001$. The two-way interaction between hemifield and position, $F(1,10) = 4.64$, $P = 0.057$, was marginal and not significant. However, there was no significant main effect for the factor location (RVF vs. LVF), $F(1,10) = 0.15$, $P > 0.05$, confirming that no difference occurs when subjects attended to the left or right lower hemifield (ADJ-1 HEM 816 vs. 822 ms, ADJ-2 HEM 822 vs. 832 ms, SEP-1 HEM 916 vs. 901 ms, SEP-2 HEM 878 vs. 849 ms).

The mean error rates of Exp.3A are presented in Fig. 6B. There were stable significant main effects for the factors hemifield, $F(1,10) = 21.08$, $P = 0.001$, and position, $F(1,10) = 6.5$, $P = 0.029$, but no significant main effect for the factor location is present, $F(1,10) = 0.54$, $P > 0.05$. Upper and lower presentation (ADJ-1 HEM 761 vs. 779 ms, ADJ-2 HEM 758 vs. 787 ms, SEP-1 HEM 795 vs. 819 ms, SEP-2 HEM 764 vs. 795 ms) led to similar reaction time patterns in the four experimental conditions.

3.3.2. Upper vs. lower visual field—Experiment 3B

Exp.3B investigated whether the results of the Exp.1 would replicate when presentations were mainly to the upper (rather than lower) visual field (see Fig. 2, right). To directly compare the four experimental conditions in the upper and lower visual field, mean RTs and error rates from the 11 subjects participated in both experiments (randomized order across subjects) were entered in three-way repeated measures ANOVAs with factors “hemifield” (1 HEM vs. 2 HEM), “position” (ADJ vs. SEP), and “location” (upper vs. lower field). Mean RTs of Exp.3B for the 11 subjects are pictured in Fig. 7A.

The three-way ANOVA showed no significant main effect for location, $F(1,10) = 0.54$, $P > 0.05$, but a reliable effect for hemifield, $F(1,10) = 5.02$, $P = 0.049$, and position, $F(1,10) = 5.87$, $P = 0.036$. Upper and lower presentation (ADJ-1 HEM 761 vs. 779 ms, ADJ-2 HEM 758 vs. 787 ms, SEP-1 HEM 795 vs. 819 ms, SEP-2 HEM 764 vs. 795 ms) led to similar reaction time patterns in the four experimental conditions.

Accuracy rates of Exp.3B are shown in Fig. 7B. The main effect for location did not reach significance, $F(1,10) = 0.27$, $P > 0.05$, while the factors hemifield, $F(1,10) = 7.08$, $P = 0.024$, and position were significant again. However, the three-way ANOVA revealed an unexpected significant interaction between the factors location and hemifield, $F(1,10) = 5.49$, $P = 0.041$. While in the lower-field condition, the hemifield effect for the separated conditions was observed for the subgroup (ADJ-1 HEM M = 12.3%, ADJ-2 HEM M = 10.3%, SEP-1 HEM M = 23.6%, SEP-2 HEM M = 11.9%), in the upper-field condition, error rates increased when stimuli were presented at separated positions both within one hemifield and across hemifields (ADJ-1 HEM M = 9.0%, ADJ-2 HEM M = 8.9%, SEP-1 HEM M = 19.1%, SEP-2 HEM M = 16.7%). Thus, the error rate data failed to support for the hemifield hypothesis in the upper visual field.

4. Discussion

4.1. Hemifield hypothesis

We found that when attended stimuli were located in one hemifield, discrimination performance for adjacent was
better than for separated stimuli. The increase in RTs and error rates within one hemifield, when attending two noncontiguous locations, is commensurate with the concept of a unitary focus of attention. The hemifield hypothesis would also predict equivalent performance in the separated and adjacent conditions when stimuli are in different hemifields. In fact, our error data support this prediction, as equivalent accuracy rates were obtained which is compatible with the "split-attention view". Of course, our data also contain a significant increase in RT in the separate condition across the hemifields as compared to the adjacent conditions, but the increase was significantly reduced compared to the separate condition within one hemifield. This is in accordance with a finding of Bichot et al. [4], who claimed that the splitting of attention may produce extra costs. Perhaps the small increase in RTs reflects the costs that are entailed by the division of attention between separated locations in space. Overall, these outcomes support the hemifield hypothesis suggesting that it may be easier to split attention between hemifields than within one hemifield.

4.2. Task difficulty hypothesis

By varying task difficulty in two different ways (Exp.2A and 2B), two major aspects can be observed: First, a bilateral field advantage can be determined for adjacent and separated positions in difficult tasks suggesting restricted attentional resources within a single hemifield as compared to both hemifields (e.g., [26]). Perhaps this advantage was not present in the easy adjacent conditions of Exp.1 because the within hemifield resources were sufficient to perform the task efficiently. Second, within one hemifield, the difference between the adjacent and separated conditions are larger in the easy task than in the difficult task. This is compatible with the task difficulty hypothesis, which suggests that complex stimuli lead to comparable performances for adjacent and separated attended locations, because intervening distracter information is not processed beyond an early stage. But, it should be noticed that only a subgroup of subjects participated in each of the experiments with higher task difficulty. From a statistical perspective, this confounds the comparison with the results of the whole group performing the first experiment. However, based on data by Kramer and Hahn [23], Awh and Pashler [2] also suggested a more relative than absolute difference between the splitting of attention within and across hemifields. Kramer and Hahn [23] used onset and offset stimuli and found evidence for split foci only in the offset conditions. The authors claimed that attention can only be flexibly deployed at two separated locations when no new objects emerge at the attended locations. However, their subjects were always slower and less accurate in the offset than in the onset conditions, irrespective of whether irrelevant distracter stimuli appeared between the relevant locations. In light of our task difficulty effects, we therefore suspect that task difficulty could have confounded the onset and offset results. This would be the case if the onset task was relatively easy compared to the nononset task. If so, the results of Kramer and Hahn [23] would be in line with our suggestion that similar performances for adjacent and separated targets can only be obtained within one hemifield under high task demands (e.g., nononset stimuli).

4.3. Visual field differences

Beside the influence of task difficulty and hemifield alignment, our Exp.3B indicates that location with respect to the horizontal meridian could be an additional factor that should be considered for visuo-spatial attentional processes. This observation, which contrasts with our failure to find differences between the right and left hemifield, could reflect differences in the spatial resolution of attention in the upper and lower fields. On the one hand, the number of subjects is smaller in these control experiments, which weakens the validity of this observation. On the other hand, we know from other studies (e.g., [21,28,38]) that the spatial resolution of visual attention in the upper visual field is generally poorer than that in the lower visual field. However, previous split attention studies do not permit a
direct comparison between upper and lower hemifield stimulation. Our own data are ambiguous in this regard. RTs show no upper–lower field difference, but higher error rates for stimuli presented in the upper hemifield. Therefore, upper vs. lower field differences could potentially confound analyses of the distribution of spatial attention. However, a lower field advantage cannot account for the overall pattern of our results. While such an advantage conceivably decreases performance in the cross-hemifield conditions of Exp.1, it should equally act in the separated and adjacent conditions. Note that both the separated and adjacent within-field stimuli straddle the horizontal meridian and that both the adjacent and separated cross-field stimuli are located in the lower field. Thus the pattern of adjacent vs. separated differences cannot be explained by perceptual visual field differences. Anyhow, future studies will have to address the question whether specific attentional effects can be generalized for the whole visual field or are specific for the hemifields.

4.4. Models of visuo-spatial attention

Do our data have implications regarding the validity of current models of visuo-spatial attention? We do not believe that any single current model of attention can adequately explain the effects observed in the current study. While models which propose a unitary focus can explain the results within one hemifield but not across hemifields, theories of multiple foci better explain the effect across hemifields, but fail to do so within hemifields. We elaborate on these points below.

4.4.1. The “unitary view”

Models of a unitary focus of attention, e.g., the zoom lens model proposed by Eriksen and St. James [14], can explain the effects within one hemifield. Attending two separated locations would require an increase in size of the focus, which should be associated with a decrease in detection performance as the attentional resources must be spread over a larger area in the visual field. However, unitary models cannot explain (i) why the difference between adjacent and separated conditions is reduced with increasing task difficulty, (ii) why a comparable discrimination performance occurs at contiguous and noncontiguous locations across hemifields, and (iii) why a bilateral field advantage was observed, despite the fact that a fixed amount of attentional resources should be predicted within any unitary focus.

In contradiction, an important alternative needs to be discussed: could an attention-shifting model (e.g., [15,48]) provide a better explanation of the experimental results? This possibility is improbable, because an advantage in shifting across hemifields is implausible. First, earlier studies (e.g., [20,42]) have, for example, indicated that shifts across the vertical meridian are more time consuming than shifts within one hemifield. Therefore, in fact, an attention-shifting model would predict a completely reversed pattern of results. Second, as in previous studies [18,23,33], the presentation time of our targets was very short (100 ms). Others (e.g., [51]) estimated that 150 ms to 250 ms are necessary to identify a stimulus at a cued location and shift to a second precued location. Thus, it would be reasonable to conclude that subjects did not have enough time to shift between locations, although this cannot be ruled out with certainty as the stimulus patterns were not masked subsequently. Third, the diminished discrimination performance in the separated compared to the adjacent condition within one hemifield contradicts a flexible shifting mechanism, unless shifting occurs in an analog fashion and is dependent on distance, which was not found in an early study by Sagi and Julesz [43].

4.4.2. The “multiple foci view”

Models in which multiple simultaneous foci of attention are proposed predict comparable results for adjacent and separated conditions, as we found when stimuli were arranged across hemifields. But these models cannot account for the differential performance for adjacent and separated conditions within one hemifield. An exception is the work from Castiello and Umiltà [7], suggesting two attentional foci when objects are located in opposite hemifields. However, none of the multiple foci models can by themselves explain the reduced difference between the adjacent and separated conditions with increasing task difficulty.

4.4.3. The “selection view”

The hybrid early–late selection model of Lavie [24] is able to explain the task difficulty effect. The study of Heinze et al. [18] could not determine whether reduced performance with increase in the attended areas’ size was due to poorer sensory processing across the whole attended region (distance effect) or to the interference from intervening stimuli within that region [37]. The effect of task difficulty bears on this issue. In our experiments, we found that discrimination performance between adjacent and separated conditions within one hemifield differs less under conditions of high task difficulty. As the size of the attended region remained unchanged between the separated conditions of the easy and difficult tasks, the difference between adjacent and separated conditions cannot be ascribed to a distance factor alone. It could also be due to a varying influence of the intervening distracter stimuli. In order to fully estimate possible differential effects of distances or distracters, a new experimental design would be necessary. In this design, for one, the distracter would be omitted in a given condition, this would allow us to measure the distance effect. Further, the performance at the distracter position should be measured explicitly (e.g., [2,32]). This would account for distracter effects. Nevertheless, in our study, the ability to ignore irrelevant distracter information seems to be directly related to the load imposed by processing of the relevant
that overt and covert attention are controlled by overlapping visuo-spatial attention and oculomotor processes, arguing
Consequently, the authors suggest a linkage between attention and overt eye movements operate together. While this could be a valid interpretation for the effects within one hemifield, the hybrid model cannot account for the hemifield effect, since Lavie [24] suggested a constant amount of attentional resources.

4.5. A modified model

Since none of the previous described models can fully explain the combined effects in our study, we propose a modified model that holds (i) that attention can be split across hemifields but forms a unitary focus within one hemifield and (ii) when attention is divided across the hemifields, there is an increase in attentional resources. Based on our results and those of others (e.g., [2,14,18,23]), we suggest the hemispheres control two partially independent attentional systems [3,7,30], which are linked by oculomotor processes [1,9,42,46]. Following the hybrid model of Lavie [24], we believe that two different processing stages should be considered. Initially, before a stimulus presentation, attention can be aligned in a unitary fashion (like a zoom lens) within each hemifield (the attention phase). When stimuli are presented (selection phase), distracter stimuli can be excluded at an earlier or later processing stage depending on task demands. Because of the increased attentional resources available when the attentional systems of both hemispheres are active, information can be processed more efficiently at an early stage of visual processing, producing the bilateral field advantage. This two-stage model can explain (i) the splitting of attention is only feasible across hemifields and (ii) the comparable performances at adjacent and separated locations within one hemifield under high task demand conditions.

4.6. The modified model in the light of current neuroanatomical concepts

The modified model is compatible with several theories which consider the physiological organization of visuo-spatial attention. For instance, Rizzolatti et al. [42] claimed that in real-life situations, shifts in covert visuo-spatial attention and overt eye movements operate together. Consequently, the authors suggest a linkage between visuo-spatial attention and oculomotor processes, arguing that overt and covert attention are controlled by overlapping neuroanatomical and physiological mechanisms. Evidence for such a functional–anatomic linkage is provided by a meta-analysis of Corbetta et al. [9] and by Culham et al. [10]. Using functional imaging methods (PET and fMRI), they found overlapping activation for overt and covert attention mechanisms in parietal and frontal regions. However, Reuter-Lorenz and Fendrich [41] expressed doubt that attention and saccadic eye movements are always controlled by the same physiological systems. Based on an analysis of the costs produced by invalid precues, they concluded that saccadic and attention systems function differently when target locations are precued with peripheral cues, but work similarly when these locations are marked by central precues. The authors suggested that the link between attention and saccades might depend upon the subsystem which is dominant for programming saccadic destinations (e.g., frontal eye fields vs. superior colliculi). In line with this hypothesis, Sereno [44,45] differentiated a subcortical and cortical system for the generation of saccadic eye movements and attention. She claimed that exogenous cues are processed by the superior colliculus, and induce reflexive saccades and fast transient attentional shifts. In contrast, endogenous cues lead to voluntary saccades and sustained attention mainly controlled by the cortical frontal eye fields and parietal structures. Both systems work in parallel and use common motor and premotor centers. Moreover, the cortical system can control the subcortical structures. In consequence, she claimed that small stimulus changes, like the nature of a cue, can radically change the operating parameters of the system. In our study central, endogenous cues were used. According to the model of Sereno, the control system would be dominantly cortical. It is therefore reasonable to examine the cortical attentional system more closely in the next section.

Both the afferent and efferent visual pathways have a bilateral crossed organization [22]. If attentional shifts are mapped onto oculomotor coordinates, then it is likely that attentional mechanisms are also controlled by the hemisphere contralateral to the relevant visual hemifield. This view is also supported by the work of Sereno and Kosslyn [46], who analyzed subjects’ discrimination performances when they had to compare two groups of characters which were either arranged within or across hemifields. Irrespective of task demands, the authors found a clear bilateral field advantage. But this bilateral field advantage disappeared when the two stimulus groups were presented sequentially. Thus, Sereno and Kosslyn suggested that when stimuli are presented simultaneously, early steps in visual processing can occur in parallel in the two hemispheres, leading to the bilateral field advantage. The authors proposed two possible mechanisms. On the one hand, the bilateral field advantage could reflect a greater amount of attentional resources, as Liederman et al. [26] suggested. Alternatively, the advantage could arise because of less intrahemispheric interference. In our study, the influence from intervening distracters within one hemifield diminished with increasing task
difficulty, and the bilateral field advantage is more pronounced in the difficult task, as both separated and adjacent conditions benefit from bilateral presentations. Thus, our results are commensurate with the first assumption of increased attentional resources. We would attribute the increase in performance when stimuli were presented across the hemifields to an increase in resources produced by dual attentional systems. However, Sereno and Kosslyn [46] also found that the hemifield effect is reduced when stimulus locations were cued exogenously, giving credence to the suggestion of Reuter-Lorenz and Fendrich [41] that the linkage between attention and saccades depends on the level of saccadic control.

Given that visuo-spatial attention is controlled by both hemispheres and more attentional resources are available across than within the hemifields, a question that arises is the extent to which these two systems are yoked. In neurologically normal subjects, interhemispheric communication is mediated by the corpus callosum, which led Arguin et al. [1] to conclude that, in normal subjects, the attentional systems of the hemispheres are yoked to form a unitary system. However, our results suggest that subjects are able to split attention across the hemifields. Interestingly, split-brain patients have a better performance than normal subjects when they attend two locations simultaneously across the hemifields [1,19,29]. This provides support for the idea that the dual attentional systems can operate independently. However, when using a precueing task requiring shifts across the vertical meridian (due to an invalid cue), Reuter-Lorenz and Fendrich [40] demonstrated that callosotomy patients were impaired compared to normal subjects. Thus, specific task demands (simultaneously attending vs. temporal shifts) produced a reversal in the performance patterns of split-brain patients. Dual stimulation leads to “increased resources” while temporal shifts lead to “hemispheric competition”. Perhaps attention can switch between two general strategies. Shifting occurs during serial hemispheric processing, but dual systems come into play when both hemispheres need to act in tandem (parallel processing). It remains to be seen if such dissociation also exists in healthy subjects.

Beyond this, we believe that the efficiency of either strategy critically depends on task difficulty. This is supported by work from Forster and Corballis [16]. They measured interhemispheric transmission time (IHTT) in callosotomized, commissurotomized, and healthy subjects. Healthy subjects presented a reduction of IHTT with increasing task difficulty (go/no-go, two-choice, three-choice task), both in color and shape discrimination tasks. A patient with anterior commissurotomy presented reversed results. Thus, it was suggested that reduction of the IHTT is due to incremental involvement of the hemispheres in task processing. This would allow parallel processing. This is in line with Banich [3] who suggested that the advantage of parallel processing is proportional to the increasing complexity of the task and that performance becomes more efficient when information is shared between the hemispheres.

Patients with right-parietal lesions show an attentional deficit (neglect) for the left visual hemispace. However, patients with left-parietal lesions show no or only transient and mild attentional deficits for the right visual hemispace. This dissociation in severity of the deficits produced by unilateral hemispheric lesions can be incorporated in our model, if we presume that the hemispheres interact but the right hemisphere is dominant for attentional control. Established models of neglect (e.g., [34]) attribute this to a right-hemispheric dominance in visuo-spatial attention. These models propose that the right hemisphere can align attention in both visual hemifields, whereas the left hemisphere is specific for the right visual hemifield. This is also supported by results of a study on split-brain patients [30]. Here, authors investigated spatial cuing effects (valid, invalid, bilateral cuing) in the left and right visual field. Interestingly, cuing effects could only be observed for stimuli presented in the left hemifield (right hemisphere). This was interpreted as evidence for “an asymmetric and independent control over attentional orienting in the cerebral hemispheres”. While the right hemisphere would allocate attention to cued locations in either hemifield, the left hemisphere was proposed to be specific for orienting in the contralateral right hemifield.

Some recent studies have sought to demonstrate this right-hemispheric dominance in normal observers. For instance, the PET study of Corbetta et al. [8] indicated that the dominance can also be observed in healthy subjects. Our model could be adjusted to incorporate such a right hemisphere dominance in attentional control. However, in the current study, subjects showed the same results when the specific conditions were aligned in the right or left hemifield, which is consistent with other results in the literature (e.g., [2,21,30]). These apparent contradictions remain to be resolved.

4.7. Physiological correlates for the modified model in human visual cortex

Recent electrophysiological measures [36] and functional imaging [33] provide neurophysiological evidence for separated attentional foci across the hemifields. Müller et al. [36] recorded frequency-coded, steady-state visual-evoked potentials (SSVEPs), which are known to be modulated by attention in extrastriate visual areas. Compared to the attended positions, they found reduced SSVEP amplitudes at unattended intermediate positions indicating that attention can be split “at an early stage of processing”. A modulation at interposed non-attended locations within one hemifield was not measured. Using fMRI, McMain and Somers [33] found enhanced activation (in V1 and V2) at separated attended locations in opposing hemifields, but no enhancement at intervening distractor locations. Their data also contain evidence for attentional modulation at inter-
mediate distracter position when separated locations were aligned in one hemifield. This modulation was weaker than at the attended locations. It cannot be clarified whether the two-peak pattern is a consequence of target selection or whether it can also be obtained during the intention phase; hence, the authors used a block design not allowing a distinction between intention and target selection phase. Overall, these results support our hypothesis that it is easier to split attention across the hemifields (no modulation at intermediate locations). Characterizing physiologically different processing stages and task difficulty effects is a topic of future research.

4.8. Perspectives

In summary, our study provides evidence that visuospatial attention is influenced by the distribution of target locations over hemifields and by task difficulty. To extend our understanding of how visual attention is spatially distributed under varying environmental conditions, further studies are needed. They should help systematically clarify the following issues: First, the effect of visual field alignment (e.g., upper/lower visual field). Second, the influence of distance effects between attended locations compared to the influence of distracter effects (under low versus high task difficulty) should be explicitly quantified.

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