



Visual attention capacity parameters covary with hemifield alignment

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ABSTRACT

The theory of visual attention (TVA; Bundesen, 1990. *Psychological Review*, 97(4), 523–547), allows one to measure distinct visual attention parameters, such as the temporal threshold for visual perception, visual processing capacity, and visual short-term memory (VSTM) capacity. It has long been assumed that visual processing capacity and VSTM capacity parameters are nearly constant from trial to trial. However, Dyrholm, Kyllingsbæk, Espeseth, and Bundesen (2011). *Journal of Mathematical Psychology*, 55(6), 416–429, found evidence of considerable trial-by-trial variability of VSTM capacity. Here we show that one cause of trial-by-trial variation is that some parameters depend on whether processing of relevant information occurs in only one hemifield or in both hemifields. Our results show that VSTM and visual processing capacities are higher when stimuli are distributed across the hemifields rather than located in the same hemifield. This corresponds to previous suggestions that parallel processing is more efficient across hemifields than within a single hemifield because both hemispheres are involved (e.g., Alvarez & Cavanagh, 2005. *Psychological Science*, 16(8), 637–643; Kraft et al., 2005. *Cognitive Brain Research*, 24(1), 453–463). We argue that the established view of a fixed visual attentional capacity must be relativized by taking hemifield distribution into account.

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1. Introduction

Visual field effects in visual attention have been studied for a long time. It is known that the distance between targets and distractors is highly relevant for attentional selection (e.g., crowding effects; Kyllingsbæk, Valla, Vanrie, & Bundesen, 2007). Moreover, it has been shown that visual attentional resolution differs between the upper and the lower visual fields, with a higher attentional resolution in the lower visual field during stationary attention (Intriligator & Cavanagh, 2001; Kraft, Pape, Hagedorf, Schmidt, Naito, & Brandt, 2007) and better performance in the upper visual field during fast attentional shifts (Danckert & Goodale, 2003; Kraft, Sommer, Schmidt, & Brandt, 2011a). In addition, several studies have revealed a bilateral field advantage in attentional tasks, such as discrimination (Serenio & Kosslyn, 1991), attentional tracking of multiple visual objects (Alvarez & Cavanagh, 2005), and covert attention on stationary objects (Kraft et al., 2005). Based on these findings, it has been proposed that parallel attentional processing is more efficient between than within the hemispheres because more or less independent processing

resources are available in the two hemispheres (Alvarez & Cavanagh, 2005; Banich, 1998; Castiello & Umiltà, 1992; Kraft et al., 2005; Kraft, Kehrner, Hagedorf & Brandt, 2011b; Mangun et al., 1994; Sereno & Kosslyn, 1991).

Although these visual field differences in visual attentional processing are known, the storage capacity of visual short-term memory (VSTM) is usually assumed to be fixed in size. For example, the theory of visual attention (TVA) proposed by Bundesen (1990) allows us to define distinct attentional parameters: temporal threshold for visual perception, visual processing capacity, VSTM capacity, selectivity of attention in target versus distractor processing, and spatial weighting.

TVA (Bundenen, 1987, 1990) seems to have been the first parallel-processing theory of attention based on the principle that Desimone and Duncan (1995) in a later, highly influential article called “biased competition.” Thus, in TVA, all possible visual categorizations ascribing features to objects *compete* (race in parallel) to become encoded into VSTM before it is filled up. Each possible categorization is supported by the current sensory evidence that the categorization is true. However, the competition is *biased* by attentional weights and perceptual biases, so that certain objects and categorizations have higher probabilities of accessing VSTM and, in this sense, being consciously perceived. The way sensory evidence and attentional biases interact is

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specified in the rate and weight equations of TVA. Thus, TVA represents a mathematical formalization of the biased competition principle.

For the purpose of TVA-based assessment of visual processing capacity (parameter C) and VSTM storage capacity (parameter K) we used a letter whole report paradigm, optimized for normal healthy subjects, with exposure durations below 250 ms and masks following the whole report display (Shibuya & Bundesen, 1988; Finke et al., 2005; Vangkilde, Bundesen, & Coull, 2011). Effective masks presented at stimulus offset are assumed to terminate visual processing of the stimuli (Sperling, 1967) thereby reducing their effective exposure duration (see Bundesen, 1990, Fig. 4). Without masks, visual afterimages prolong the effective exposure of a display. Thus, the use of masks in our whole report experiment permitted accurate estimates of the temporal threshold (the longest ineffective exposure duration, t_0) and the visual processing capacity C (objects per second).

We estimated C , K , and t_0 by the computational procedures first described by Shibuya and Bundesen (1988). The procedures assume that a letter from the stimulus display can be correctly reported without guessing if, and only if, the letter becomes encoded into VSTM. This assumption seems plausible when, and only when, responding is as easy as naming a letter. The assumption implies that performance shows limitations reflecting the properties of VSTM rather than the properties of verbal short-term memory or implicit speech. The way the number of items correct in whole report (the score) increases with the exposure duration agrees with this implication. The score is critically dependent on the stimulus-onset asynchrony (SOA) between the target display and the mask. When the SOA is less than t_0 , the score via non-guessing appears to be zero. As the SOA exceeds t_0 , the mean score initially increases at a high rate of about one letter for every 5–30 ms of SOA, and then levels off as it approaches a span of around four items, or the number of items in the stimulus, whichever is smaller (cf. Dyrholm, Kyllingsbæk, Espeseth, and Bundesen, 2011; Finke et al., 2005; Merikle, Coltheart, & Lowe, 1971; Shibuya & Bundesen, 1988; Sperling, 1960, 1963, 1967; Townsend & Ashby, 1983, Chapter 11; also see Luck & Vogel, 1997). By further increase in the exposure duration, the score increases only very slowly, at a rate that is comparable to the estimated rate of implicit speech (about 150 ms per letter; Landauer, 1962). This slow rate of increase presumably reflects the maximum rate of recoding into implicit speech (read-out from VSTM into verbal short-term memory; Coltheart, 1972). Thus, both the estimated limitation on storage capacity (four items rather than the magical number 7 of Miller, 1956) and the estimated rate of encoding (initially 5–30 ms per letter rather than 150 ms per letter) suggest that performance shows limitations reflecting the properties of VSTM rather than the properties of verbal short-term memory or implicit speech.

Dyrholm et al. (2011) introduced a general concept of trial-by-trial variability of TVA parameters and found evidence that VSTM capacity varies more than traditionally assumed. The aim of the present study was to test whether visual attentional capacity parameters covary with hemifield alignment. Specifically we hypothesize that a bilateral field advantage in visual working memory (Umemoto, Drew, Ester, & Awh, 2010; Delvenne & Holt, 2012) generalizes to the VSTM capacity parameter K as measured by TVA. That is, VSTM capacity is higher when a whole report display is distributed across the two hemifields compared to only one hemifield. Furthermore, TVA allows for the separation of VSTM capacity parameter K and visual processing capacity parameter C . The present study tested whether a bilateral field advantage can also be obtained for processing capacity parameter C . In this experiment, we directly measured the effect of hemifield alignment in whole reports of letters from brief visual displays.

Stimulus positions and eccentricity were kept constant to control for crowding effects (Kyllingsbæk et al., 2007). Distinct attentional parameters were estimated using the TVA fitting procedure developed by Dyrholm et al. (2011), see also Kyllingsbæk (2006).

2. Material and method

2.1. Participants

Sixteen healthy subjects (15 females, 1 male, *mean age* = 24.0 years, *SD* = 5.6 years) participated in the study. Subjects were recruited at the Department of Psychology at the Humboldt University of Berlin. Subjects fulfilled the following criteria: no history of neurological, psychiatric or ophthalmological pathology, no alcoholism or mental deterioration and no acute or chronic medication affecting the central nervous system. All subjects had normal or corrected to normal visual acuity (near and far visus better than 0.8) and were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971). Written informed consent was obtained from all participants and the examination was conducted in conformity with the declaration of Helsinki. All subjects were reimbursed for their participation.

2.2. Experimental procedure

The method was similar to that of Vangkilde et al. (2011). Using a whole report paradigm (Sperling, 1960), in which the task was to report as many of the displayed letters as possible, distinct attentional parameters such as the temporal threshold for visual perception (parameter t_0), the visual processing capacity (parameter C ; i.e., information accumulation rate in number of letters per second) and the visual span/VSTM capacity (parameter K ; i.e., maximum number of reported letters) could be estimated (see also Shibuya & Bundesen, 1988).

The study was conducted in a dimly lit room. Stimuli were presented on a 17-in PC monitor screen (1280 × 1024-pixel resolution; 60 Hz refresh rate) using Presentation (Neurobehavioral Systems, Inc., Albany). Subjects were seated 90 cm from the screen. The head was stabilized by a chin rest to ensure a fixed viewing distance and to avoid head movements.

The TVA hemifield test took approximately 90 min (648 trials) to complete after 20 practice trials. Each subject completed three blocks (108 trials each) of 1-hemifield trials (1HEM) and 2-hemifield trials (2HEM), respectively. The general design of each trial and the hemifield conditions are outlined in Fig. 1. In all trials participants were instructed to maintain fixation on a red fixation cross (0.4° high × 0.4° wide), centered in the middle of the screen on a black background. The fixation cross was presented for 1000 ms and was followed by a 100-ms blank (black) screen before the letters were displayed. Six different letters (1.2° high × 1.1° wide) were randomly chosen from a reduced alphabet of 20 letters (ABDEFGHJKLMNPRSTVXZ) and presented on an imaginary circle ($r = 4.8^\circ$ visual angle, spacing between center of positions 2.8°) for a variable exposure duration (16, 33, 66, 100, 160, or 250 ms). The letter display was followed by a 500 ms mask

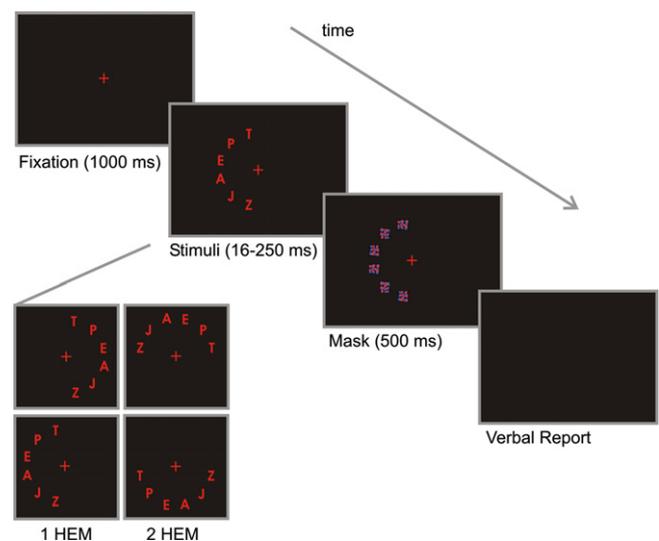


Fig. 1. Experimental procedure. The timing of a single whole report trial (above) and one-hemifield (1HEM) and two-hemifield (2HEM) letter displays (below) are illustrated.

(six masks, 1.5° high \times 1.5° wide, made from red and blue letter fragments, see Vangkilde et al., 2011). After the presentation, subjects gave a nonspeeded verbal report of the identities of the stimulus letters. The letters could be reported in arbitrary order. Subjects were instructed to report as many letters as possible but refrain from pure guessing. Verbal response was recorded with a microphone and typed in by the experimenter seated outside the room. Half of the subjects started with the 1-hemifield blocks, the other half started with the 2-hemifield blocks. Distinct trial types within each block were presented equally often and in randomized order.

2.3. Data analysis

We tested our hemifield hypothesis by formal model comparison. For this purpose, the TVA parameters t_0 (the longest ineffective exposure duration of a visual stimulus), K (the capacity of VSTM), and C (the processing capacity, i.e., the total visual categorization rate) were estimated for the 1HEM and the 2HEM conditions separately to represent the hypothesized hemifield model, and for all trials combined to represent the standard TVA model (the null model). Estimation was achieved using the maximum likelihood fitting procedure of Dyrholm et al. (2011). Any reported letter that had not been displayed on the corresponding trial (i.e., any false alarm) was discounted as evidence of VSTM encoding (see also Kyllingsbæk, 2006).

For each individual fit, spatial attentional biases were taken into account. Specifically, in testing the hemifield model, we estimated the ratio between the attentional weights of letters in the upper versus the lower quadrants for either 1HEM condition (one ratio for left-sided and one for right-sided displays) and the ratio between the weights of letters in the left versus the right quadrants for either 2HEM condition (one ratio for upper and one for lower displays). In testing the null model, we estimated the ratios between the attentional weights of letters in the four quadrants (three degrees of freedom). For debiased estimation of K , its marginal probability mass function was estimated using 5 degrees of freedom per fit (in our case, where six letters were shown in each display, the five degrees of freedom correspond to the extremely weak assumption that $K > 0$; for more details see Dyrholm et al., 2011). Each of the K values we report for individual

subjects equals the mean of the probability distribution for the given subject. Thus, the null model used 10 degrees of freedom (3 for spatial attentional weight, 5 for K , 1 for t_0 , and 1 for C). The hemifield model used 18 degrees of freedom (4 for spatial attentional weight, 10 for K , 2 for t_0 , and 2 for C).

The performance of one representative participant is illustrated in Fig. 2A. The graph displays the mean number of correctly reported letters as a function of exposure duration (circles for 1HEM data, diamonds for 2HEM data). As can be seen, the number of letters reported by the participant ascended steeply with increasing exposure duration and reached its maximum at around four letters. The smooth curves display expected values given by the hemifield model (i.e., by modeling the 1HEM and the 2HEM conditions separately). The temporal threshold for visual perception t_0 was 13 ms (starting point on the abscissa, no letters were reported below this point), the slope of the curve at t_0 equals the visual processing capacity C , and the asymptote of the curve is the expected VSTM capacity K .

To test whether the hemifield model provided significantly better fits compared to the null model we used likelihood ratio tests (LRT) both on the single subject level and on the group level (the null model was nested under the hemifield model).

Further statistical analysis was carried out using SPSS Software (Version 19). Paired t -tests were used to evaluate the difference between hemifields (1HEM vs. 2HEM) for the hemifield model parameters t_0 , C and K . Although testing order 1HEM-2HEM and 2HEM-1HEM was counterbalanced across subjects, we computed independent t -tests for TVA parameters t_0 , C and K for comparing the eight subjects who started with the 1HEM blocks with those who started with the 2HEM blocks. Differences were considered to be statistically significant at the 0.05 level.

To test for effects of letter position, we computed the frequency of letter report for each position within the four types of whole report display (left, right, upper or lower visual field). To test for spatial clustering effects we computed the frequency of co-reports for every combination of position within the four types of whole report display. Significance levels were derived with respect to a null hypothesis which stated that co-reports had happened at a uniform rate given the mean score per subject, display type, and exposure duration. For this purpose, samples were taken from the null by permutation bootstrapping: Each participant's trial-by-trial report pattern was permuted a number of times respecting position, display

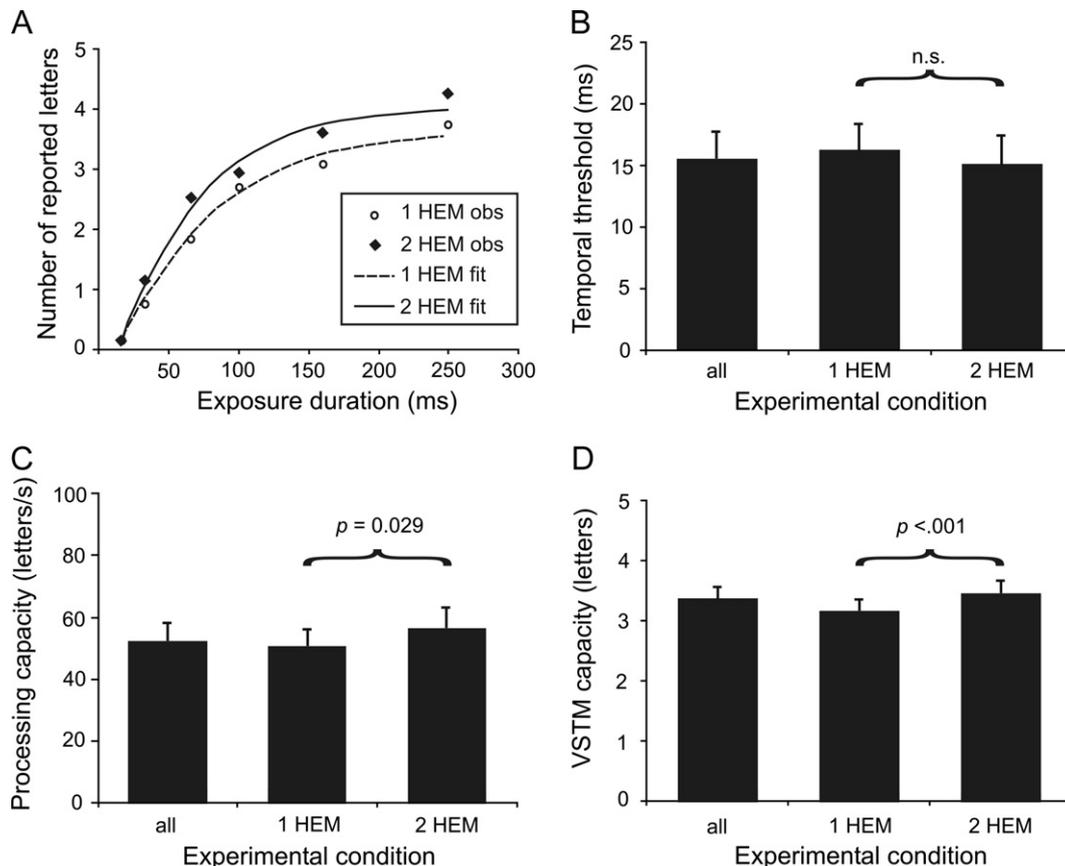


Fig. 2. TVA parameter estimates. (A) Whole report performance in one-hemifield (1HEM) and two-hemifield (2HEM) conditions for a representative subject (subject 07). The mean numbers of correctly reported letters are shown as functions of exposure duration (circles=1HEM, diamonds=2HEM). Curves represent TVA-based fits to the observations (dashed line=1HEM, solid line=2HEM). Panels (B)–(D) display TVA parameter estimates across all trials (all), for the one-hemifield trials (1HEM), and for the two-hemifield trials (2HEM). (B) The temporal threshold for visual perception t_0 . (C) The visual processing capacity C . (D) The capacity of visual short-term memory K . The p values indicate significant ($p < 0.05$) or non-significant (n.s.) differences, as revealed by paired t -tests. The error bars indicate standard errors of the means.

type, and exposure duration such that each permutation preserved the mean score per position, display type, and exposure duration. Significance levels were estimated per display type by counting the number of permutations for which the permuted co-report frequency was at least as extreme as the observed co-report frequency, then by dividing by the total permutation count.

Table 1
Percent hit and false alarm rates of distinct letter stimuli for the 1HEM and 2HEM conditions, respectively.

Letter type	Hit rate (%) (1HEM/2HEM)		False alarm rate (%) (1HEM/2HEM)	
A	38	48	4	4
B	26	32	2	2
D	30	32	3	1
E	27	34	6	9
F	20	24	2	2
G	30	36	3	3
H	22	21	7	9
J	39	42	3	4
K	21	23	6	4
L	44	48	7	7
M	32	35	19	14
N	17	20	11	10
O	47	51	9	8
P	29	35	6	8
R	23	28	6	7
S	32	40	5	6
T	39	44	4	6
V	28	33	2	3
X	21	24	5	3
Z	30	40	3	5
Mean	29.8	34.5	5.7	5.8

Table 2
Overall frequencies and detection rates as a function of exposure duration.

Exposure duration	Report Frequency (1HEM/2HEM)		Hit rate (%) (1HEM/2HEM)		False alarm rate (%) (1HEM/2HEM)	
16	126	167	2	3	4	4
33	661	746	13	14	5	6
66	1515	1831	29	35	7	7
100	1938	2243	37	43	7	7
160	2346	2648	45	51	6	5
250	2702	3077	52	59	5	5

Table 3
Individual results of likelihood ratio test (LRT) and individual attentional parameter estimates for the null model (all) and the hemifield model (1HEM/2HEM). Parameter t_0 is measured in milliseconds, C is measured in letters per second, K is measured in number of letters.

Subject no.	LRT p	t_0 all	t_0 1HEM	t_0 2HEM	C all	C 1HEM	C 2HEM	K all	K 1HEM	K 2HEM
01	0.00	11.19	15.00	8.86	86.35	82.24	102.23	4.35	3.74	4.52
02	0.00	13.88	12.08	15.31	81.75	77.46	87.40	4.07	3.81	4.25
03	0.00	31.54	31.22	32.11	27.68	20.83	41.38	2.50	2.34	2.48
04	0.02	15.81	15.58	16.47	51.44	46.13	61.51	3.21	3.23	3.14
05	0.00	14.14	13.34	14.87	25.77	23.47	29.65	2.35	1.96	2.55
06	0.11	13.97	15.03	12.55	31.05	34.06	26.85	1.96	2.06	1.90
07	0.00	13.07	13.07	13.11	52.55	47.02	58.51	3.92	3.72	4.06
08	0.41	28.95	30.92	26.91	55.56	55.60	55.60	3.29	3.36	3.23
09	0.00	22.14	26.60	18.27	48.32	51.09	48.12	3.06	2.80	3.23
10	0.00	27.54	27.89	27.82	63.27	63.08	68.05	3.49	3.12	3.69
11	0.02	10.07	10.20	10.15	17.83	16.01	20.08	2.68	2.74	2.66
12	0.00	12.56	10.52	14.87	48.74	51.82	47.19	3.07	2.93	3.14
13	0.00	10.71	12.56	9.36	107.86	97.15	120.39	4.82	4.64	4.97
14	0.60	15.21	14.80	15.63	46.27	46.86	47.17	3.98	3.68	4.03
15	0.10	13.31	12.91	14.11	36.29	39.45	36.43	2.83	2.52	3.00
16	0.16	-6.01	-2.90	-9.13	55.79	57.06	54.78	4.21	4.00	4.40
Mean (SE)		15.51 ± 2.22	16.18 ± 2.22	15.08 ± 2.33	52.28 ± 5.96	50.58 ± 5.54	56.58 ± 6.80	3.36 ± 0.20	3.17 ± 0.19	3.45 ± 0.21

3. Results

The percent hit and false alarm rates of different letters at all positions for the 1HEM and 2HEM trials are summarized in Table 1. All letters were used about 1500 to 1600 times. We found almost identical false alarm rates for the 1HEM and 2HEM conditions (5.7% and 5.8%, respectively) while the hit rate was higher in the 2HEM condition than in the 1HEM (34.5% and 29.8%, respectively). Across both conditions the hit rate was highest for the letters O, L and A, while lowest for the letters N, H and F. The false alarm rate was highest for the letters M, N and O and lowest for the letters B, F and D. The noticeably higher false alarm rates for the letters M and N (cf. Table 1) were not accompanied by higher hit rates. To assess potential confusability between M and N as an explanation for this, we analyzed responses across trials in which either an M or an N (but not both) were presented. Of the M-trials, 4.2% were falsely reported with an N while 32.4% were correctly reported. In contrast, of the N-trials, 8.2% were falsely reported with an M while 18.7% were correctly reported. So, confusability between M and N seems a reasonable explanation for the high false alarm rates in M and N trials and the low hit rate in N trials.

Table 2 displays the hit and false alarm rates for 1HEM and 2HEM trials as a function of exposure duration. As expected, hit rates increased with increasing exposure duration both for the 1HEM and 2HEM conditions. The false alarm rates were slightly higher at the intermediate exposure durations compared to the shortest and longest exposure durations in both the 1HEM trials and the 2HEM trials. While hit rates for the 2HEM condition were higher for all exposure durations, the false alarm rates were comparable for the 1HEM and 2HEM conditions and both followed the pattern of higher false alarm rates at intermediate exposure durations recently discussed by Kyllingsbæk, Markussen, and Bundesen (2012).

Individual parameter estimates obtained from the TVA fitting procedure are summarized in Table 3. Mean fitted parameter values for the null-hypothesized model that uses a common parameter set for all trials, as well as for the hemifield model that uses distinct parameter sets for the 1HEM and the 2HEM trials, are displayed in Fig. 2 (Fig. 2A shows the values for one representative participant).

In formal model comparison on the group level, the hemifield model was significantly better than the null model ('all' cf. Table 3) which shares TVA parameters between the 1HEM and

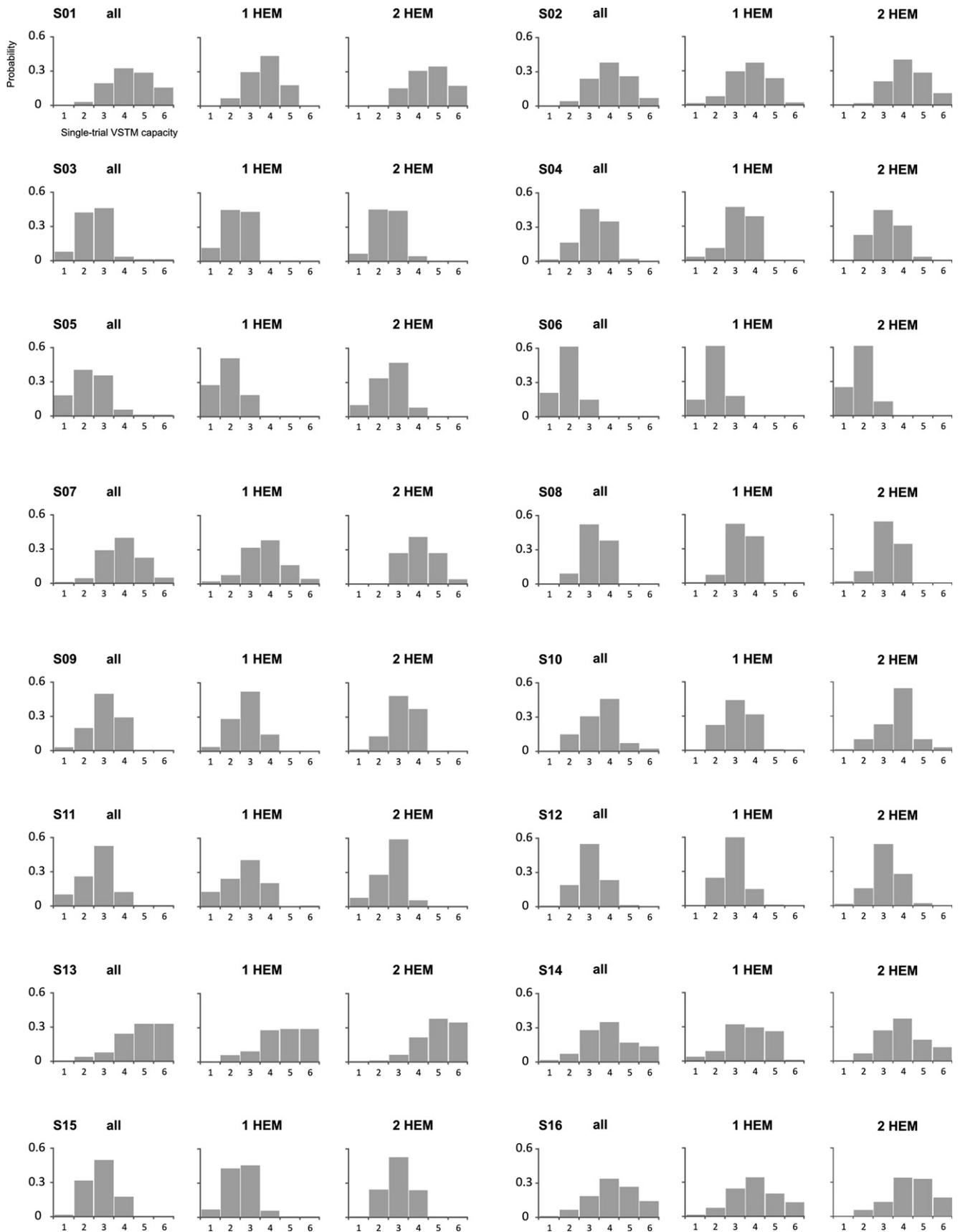


Fig. 3. Estimated probability distributions of single-trial VSTM storage capacity for individual subjects across all trials (all, all exposure durations), unilateral trials (1HEM, all exposure durations), and bilateral trials (2HEM, all exposure durations). Histograms indicate the probability (y -axis) that the VSTM storage capacity has a value of 1,2,3,4 or 6 (x -axis).

the 2HEM conditions (likelihood ratio test on the group level, $-2 \log \lambda = 453.1$, $p [> \chi^2(128)] < 0.001$). On the single subject level the hemifield model was significantly better in 11 subjects (see Table 3).

T-test based statistical analyses showed no difference between 1HEM and 2HEM trials with respect to the temporal threshold for visual perception, t_0 ; $t(15) = 1.21$, $p > 0.05$. However, visual processing capacity C was significantly higher when targets were

distributed across the left and right hemifields rather than presented in the same hemifield, $t(15) = 2.46$, $p = 0.027$ (2HEM mean 56.58 ± 6.80 SE; 1HEM mean 50.58 ± 5.54 SE). VSTM capacity K was also significantly higher in the two-hemifield condition compared with the one-hemifield condition, $t(15) = 4.07$, $p < 0.001$ (2HEM mean 3.45 ± 0.21 SE; 1HEM mean 3.17 ± 0.19 SE). This was also evident in the individual estimated single-trial VSTM storage capacity functions: To illustrate, the estimated

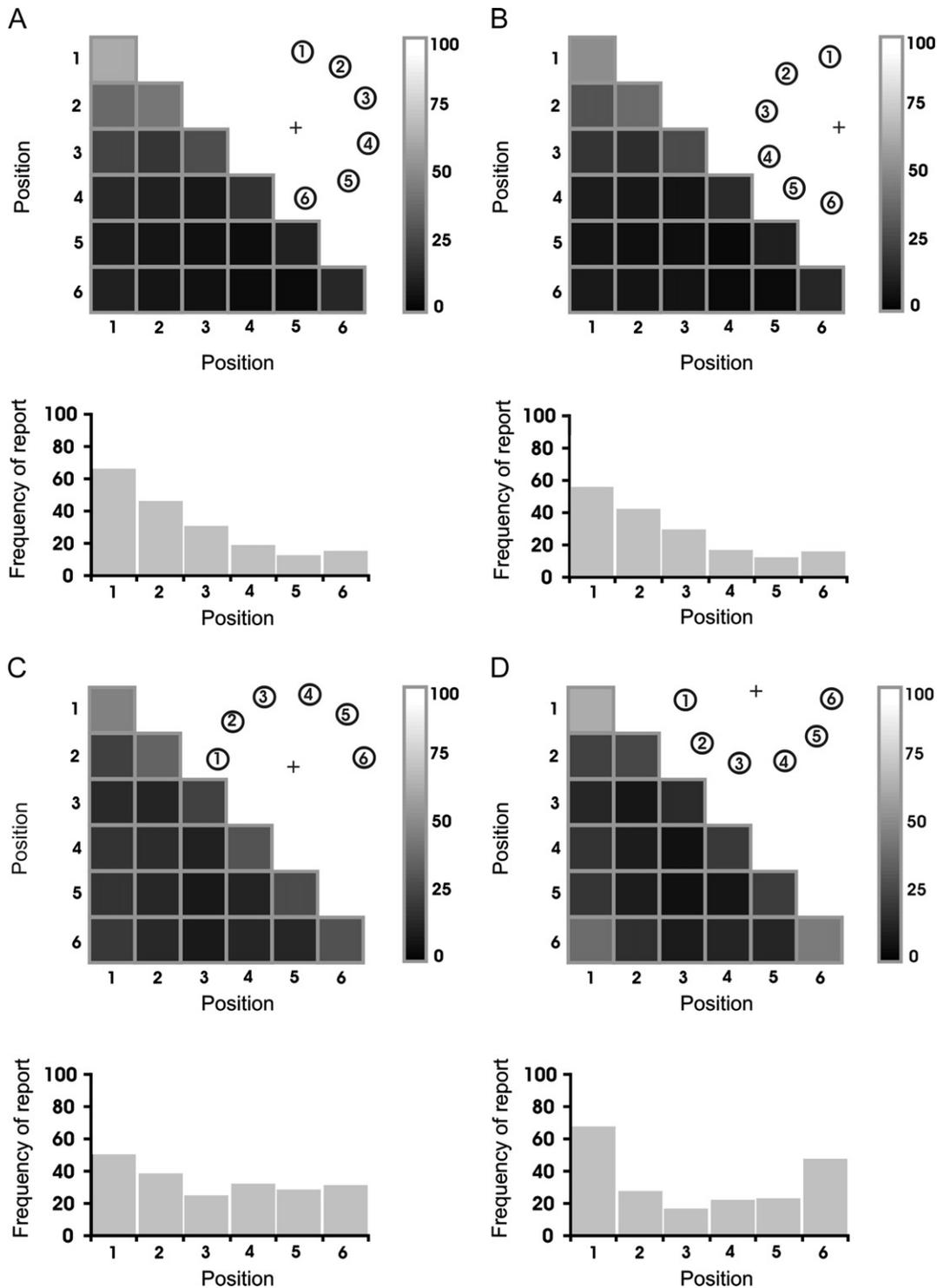


Fig. 4. Frequencies of correct letter reports at different display positions. Panels (A)–(D) show the frequencies of correctly reported letters as percentages at individual positions (Positions 1–6) in the right (A), left (B), upper (C) and lower (D) display conditions. The six cells on the diagonals of each of the four box diagrams indicate the frequencies of correct letter reports at Positions 1–6, respectively, on a gray scale (0 to 100%). These frequencies of report are also depicted in the lower histograms as percentages. The 15 remaining boxes in each of the four box diagrams show the frequencies of co-reports for all pairs of positions.

probability distributions of single-trial VSTM storage capacity for all 16 subjects are displayed in Fig. 3. For both 1HEM and 2HEM the probability histograms are unimodal. Histograms are distributed to the right in 2HEM compared to 1HEM, i.e., single-trial VSTM capacity was higher in 2HEM than 1HEM (except subjects S04, S06, S08 and S11).

As differences between the upper and lower visual fields in attentional processes have been reported previously (see Section 1), we tested whether the bilateral field advantages could be replicated by separate analyses of trials with upper and lower stimuli, respectively. The VSTM capacity parameter K was significantly higher both for upper and lower stimuli compared to the 1HEM condition, as tested by separate paired t -tests [upper visual field mean 3.49 ± 0.21 SE, 1HEM mean 3.16 ± 0.19 SE, $t(15) = -4.2$, $p < 0.001$; lower visual field mean 3.40 ± 0.23 SE, 1HEM mean 3.16 ± 0.19 SE, $t(15) = -2.7$, $p = 0.017$]. Also the visual processing capacity parameter C was significantly higher both for upper and lower stimuli compared to the 1HEM condition [upper visual field mean 58.21 ± 7.74 SE, 1HEM mean 50.61 ± 5.56 SE, $t(15) = -4.2$, $p < 0.001$; lower visual field mean 57.28 ± 6.24 SE, 1HEM mean 50.61 ± 5.56 SE, $t(15) = -2.7$, $p = 0.017$].

Fig. 4 illustrates position-specific frequency analyses for each display type (right, left, upper and lower visual field). For both display types in the 1HEM condition (right and left visual field) clustering effects for letters in the upper quadrants were indicated by the relatively high frequency of position co-reports

(Fig. 4A and B, respectively). Bootstrapping analysis based on 10^5 permutations quantified this finding (see Fig. 5): There was a tendency toward co-reports *within* quadrants for the 1HEM conditions, particularly between the two topmost positions in the right 1HEM display condition (significant, $p < 0.001$) and between the two topmost positions in the left 1HEM condition (not significant, $p = 0.14$). In contrast, in the 2HEM conditions the indication of co-reports tended to be found *across* quadrants (most notably between positions 1 and 5 in the down 2HEM condition, not significant, $p = 0.08$).

Frequency of correct letter report was highest at the upper end-position (Position 1) followed by the neighboring positions (Positions 2 and 3) within the upper visual field quadrants. The overall number of correctly reported letters was higher in the right compared with the left visual field condition (right visual field 4922 letters correctly reported; left visual field 4366 letters correctly reported). In contrast, correct letter reports were more equally distributed between visual field quadrants in the 2HEM conditions (Fig. 4C and D, respectively). For the upper visual field condition the distribution of letter reports was fairly uniform across positions, whereas in the lower field condition, the end-letters (Positions 1 and 6) near the midline were reported more frequently. However, the overall number of correctly reported letters was similar for the upper versus the lower visual field conditions (upper visual field 5395 letters correctly reported; lower visual field 5317 letters correctly reported), which suggests

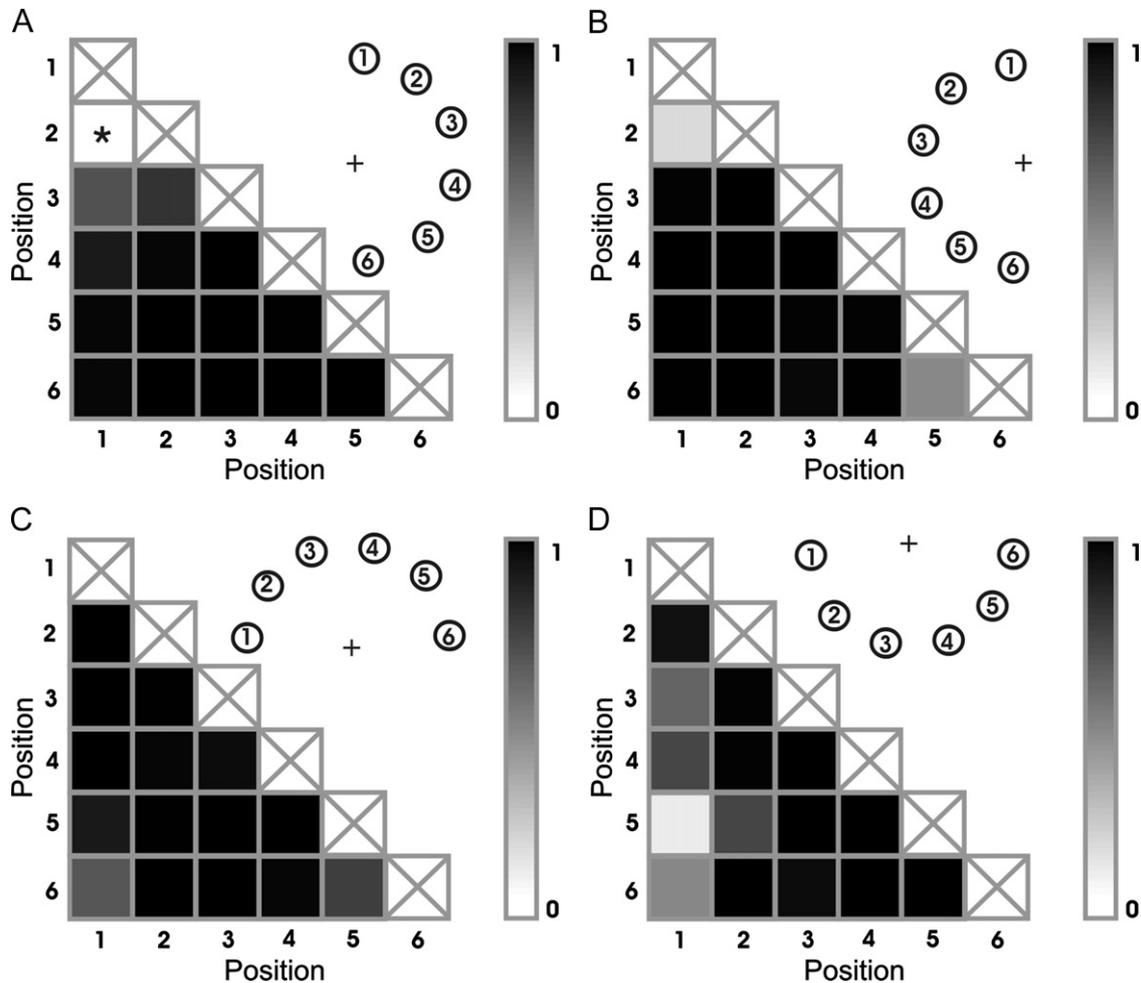


Fig. 5. Bootstrap derived values for the tendency to report positions in combination (co-reports). Each p value (0 to 1 on a grayscale) indicates the probability that the observed frequency of co-reports would happen by chance given the participants' performance in each condition (a * indicates statistical significance at the 5% level). In the 1HEM conditions (right and left) co-reports tended to happen *within* quadrants, whereas in the 2HEM conditions (up and down) they tended to happen *across* quadrants.

that the higher report frequency for the end-positions in the lower visual field may be due to differential attentional weighting. To assess the potential estimation bias caused by using too few independent parameters for representing attentional weights, we reanalyzed the lower visual field trials of the 2HEM condition using two additional spatial attentional weights for the end-positions (two extra degrees of freedom) per fit. The fits were significantly better (by a likelihood ratio test on the group level, $-2 \log \Lambda = 2685.1$, $p [> \chi^2(32)] < 0.001$) and yielded higher estimates of C (average increase of 16.5 Hz) and K (average increase of 0.2). Thus, our hemifield model seems to yield conservative estimates of the differences between the 1HEM and the 2HEM conditions.

We found no significant differences between subjects starting with the 1HEM blocks (SEQ1) and subjects starting with the 2HEM blocks (SEQ2). For parameter t_0 in the 1HEM condition, $t(14) = 0.30$, $p > 0.05$, SEQ1 mean 16.86 ± 2.70 SE, SEQ2 mean 15.49 ± 3.70 SE. For parameter t_0 in the 2HEM condition, $t(14) = 0.11$, $p > 0.05$, SEQ1 mean 15.11 ± 2.68 SE, SEQ2 mean 15.01 ± 4.00 SE. For parameter K in the 1HEM condition, $t(14) = -0.56$, $p > 0.05$, SEQ1 mean 3.06 ± 0.32 SE, SEQ2 mean 3.27 ± 0.22 SE. For parameter K in the 2HEM condition, $t(14) = -0.09$, $p > 0.05$, SEQ1 mean 3.43 ± 0.34 SE, SEQ2 mean 3.47 ± 0.29 SE. For parameter C in the 1HEM condition, $t(14) = -0.61$, $p > 0.05$, SEQ1 mean 47.16 ± 10.38 SE, SEQ2 mean 54.01 ± 4.55 SE. For parameter C in the 2HEM condition, $t(14) = 0.09$, $p > 0.05$, SEQ1 mean 57.10 ± 12.62 SE, SEQ2 mean 56.07 ± 6.22 SE.

4. Discussion

In the present study we investigated visual attention in single and dual hemifields using a TVA paradigm based on whole report of unrelated letters from unilateral and bilateral displays. The paradigm allowed estimation of the temporal threshold for visual perception, the visual processing capacity, and the VSTM storage capacity for single and dual hemifields separately. Visual thresholds are known to be highly symmetrical for the left and the right visual field, both in normal subjects as well as in most patients (Habekost & Rostrup, 2006), and we did not find a significant difference in the temporal threshold for visual perception between unilateral and bilateral displays. We did, however, find that the visual processing capacity and the VSTM capacities were higher when targets occurred in both hemifields rather than being restricted to a single hemifield. Thus, our findings show that visual attention capacity parameters covary with hemifield alignment.

Our subjects were instructed to report as many stimulus letters as possible but refrain from pure guessing. The results showed few intrusion errors (false alarms) at the shortest and the longest exposure durations, but more intrusions at intermediate exposure durations. This finding is similar to findings of Kyllingsbæk et al. (2012). In two experiments the proportion of correct responses increased with increasing exposure duration while erroneous responses were highest for intermediate exposure durations. The authors showed that a Poisson counter model provided close fits for both correct reports and erroneous reports. In the view of Kyllingsbæk et al. (2012) this model is an extension of the TVA model for tasks in which guessing has to be taken into account: It is assumed that categorizations in VSTM may be confirmed if the same categorization is repeated (sampled again) and responses can be based on the number of such confirmations.

Visual processing capacity has been investigated less thoroughly than VSTM storage capacity. In TVA, the parameters C and K are defined as independent parameters, although the two parameters correlate about 0.40 empirically (Finke et al., 2005).

Studies in stroke patients have shown that anatomically, C and K depend on overlapping cortical networks (Habekost & Rostrup, 2006, 2007; Peers et al., 2005). Nevertheless, it has been shown that the level of alertness can affect visual processing capacity without necessarily affecting VSTM capacity (Matthias et al., 2010).

Lesion studies show that reductions in visual processing capacity and VSTM capacity occur in both hemifields after unilateral lesions (Duncan et al., 1999; Habekost & Rostrup, 2006, 2007; Peers et al., 2005; see Habekost & Starrfelt, 2009, for a review). For instance, the study of Duncan et al. (1999) used TVA to investigate VSTM capacity for the left and right hemifield separately in stroke patients with right-sided parietal lesions. Patients showed VSTM capacity reductions in both sides. As for the visual processing capacity, lesion studies have reported differences between the contra- and ipsilesional hemifield with the deficit more pronounced in the contralesional field (e.g., Duncan et al., 1999; Peers et al., 2005; Habekost & Rostrup, 2006, 2007). Future lesion studies should go beyond changes for the contra- or ipsilesional field separately, and address how processing capacity and VSTM capacity parameters change for one and two hemifield presentation after lateralized lesions.

4.1. Crowding

Kyllingsbæk et al. (2007) used TVA to investigate the effect of crowding or spatial separation between stimuli (*lateral masking*). The model proposed by the authors was based on both TVA and NTVA, a neural interpretation of the theory of visual attention and short-term memory (NTVA; Bundesen, Habekost, & Kyllingsbæk, 2005). The number of reported letters increased with spatial separation of letters, and it was suggested by the authors that crowding due to competitive interactions within receptive fields could explain the differences in visual capacity parameters. In the present study, stimulus positions, stimulus spacing, and stimulus eccentricity were identical between one and two hemifield conditions. One could argue that crowding is lower across the hemifields, as only three positions were aligned in each hemifield. But note that within one hemifield, three positions were presented above and below the horizontal meridian, respectively. Thus, positions were processed either below or above the calcarine sulcus, respectively, making it unlikely that these positions were processed within the same receptive fields in a lower level cortical area.

However, we found a preference for the upper compared to the lower positions in the one hemifield condition. As described in the introduction varying preferences for the upper or lower visual field have been reported in several previous studies (Danckert & Goodale, 2003; Intriligator & Cavanagh, 2001; Kraft et al., 2007; Kraft et al., 2011a). The present finding underlines again that specific upper or lower field preferences depend on the type of visual attention task and have to be tested experimentally. Moreover, stimuli were aligned more vertically in the one hemifield condition and more horizontally in the two hemifield condition. One could argue that performance was worse simply because items were relatively “vertically aligned” in the one hemifield condition, and relatively “horizontally aligned” in the two hemifield condition which could make a difference in lateral interference. However, a previous study (Feng, Jiang, & He, 2007) has consistently shown opposing results: for distinct stimulus types (letters, line segments) crowding effects were significantly stronger in horizontally rather than vertically arranged stimulus displays. It is therefore unlikely that the hemifield effect can be explained by differences in crowding. Moreover, previous studies have shown that the bilateral field advantage cannot be explained by differences in horizontal and vertical target alignment, for example,

during a visual orientation discrimination task (Chakravarthi & Cavanagh, 2009) or during a visual enumeration task (Delvenne, Castronovo, Demeyere, & Humphreys, 2012). In control experiments both studies showed that the bilateral field advantage could not be attributed to a horizontal alignment advantage in bilateral displays.

The present data suggest that we cannot measure a general spatial bias for a specific position in our experimental setup. Apparently, the frequency of report of letters at a particular position in the visual field depends not only on the absolute position in the field but also on the relative position, that is, the position of the letters relative to the positions of other letters in the display. This corresponds to findings of Shipp (2011), using similar positions in a color-conjunction search task: Beside a bilateral field advantage, Shipp (2011) also found that the position of a target within a visual field quadrant was a major determinant of response time and that this effect varies between the upper and lower visual field.

However, a preference for end-letter positions (particularly for the upper field position in the one-hemifield condition and in the lower field subcondition of the two-hemifield condition) was evident. Presumably, the end-letter positions are the positions with minimum crowding. Our refitting of the data, taking into account the end-letter status of some positions, suggested that the TVA capacity parameters were underestimated in the lower visual field condition. Thus, the estimated bilateral field advantages showed some increase when we corrected for effects of placement at end-positions.

The apparent clustering effect within the upper visual field in the 1HEM conditions suggests a focus on the stimuli in a single quadrant of the visual field, while attention may have been more equally distributed across two visual field quadrants in the 2HEM conditions. Future studies investigating attentional performance for distinct visual field quadrants or hemifields should control for clustering effects.

4.2. Hemispheric resource model

The results agree with a hemispheric resource model of parallel visual attentional processing (e.g., Alvarez & Cavanagh, 2005; Kraft et al., 2005). Several studies have revealed a robust bilateral field advantage in attention tasks that require simultaneous tracking of multiple objects (Alvarez & Cavanagh, 2005) or discrimination (Sereno & Kosslyn, 1991; Kraft et al., 2005; 2007). Several authors have suggested independent attentional resources for the hemispheres, resulting in the use of more attentional processing resources in parallel attentional processing of bilateral displays, compared to unilateral displays. However, these models suggest hemisphere-specific resources on an early level of visual processing, and until recently it has been unclear whether hemisphere specificity is also intrinsic to later stages, such as memory storage. Umemoto et al. (2010) and Delvenne and Holt (2012) found evidence of a bilateral field advantage in visual working memory, showing that even later stages of visual attentional processing are influenced by hemifield/hemisphere-specific presentations. Our results agree with these findings. VSTM capacity is higher, although it is not twice as high as in unilateral displays, showing that VSTM is not organized into two completely independent storages for the hemispheres. Alvarez and Cavanagh (2005) found that even though tracking capacity nearly doubles in an attentional tracking task in bilateral compared to unilateral displays, maximal VSTM storage capacity is not twice as large in bilateral displays as unilateral displays. This is also in agreement with the findings of Umemoto et al. (2010), which suggest that there is a bilateral field advantage for the probability of storage in visual working memory and not for the resolution of the stored representations. However, Umemoto et al. (2010), as well as Kraft et al. (2005) noted that the bilateral field advantage seems to be stronger when there is strong interference

from distractors. In both the present study and Umemoto's paradigm (Umemoto et al., 2010), all stimuli were relevant (i.e., targets), in contrast to Alvarez and Cavanagh's task (Alvarez and Cavanagh, 2005), in which relevant stimuli were tracked among irrelevant distractors. We agree with Umemoto et al. (2010) that future studies must clarify whether the magnitude of the bilateral field advantage in visual attention capacity parameters is modulated by the amount of distractor interference.

It is worth noting that no evidence for a bilateral field advantage has been found in the color domain (e.g., Delvenne, 2005), and it has therefore been proposed that the bilateral field advantage affects visual attention for dorsal rather than ventral stream visual features (Alvarez & Cavanagh, 2005; Umemoto et al., 2010). The present results challenge this hypothesis, as our letter task necessitates identification and ventral stream processing similar to a color identification task. However, some authors have objected that the use of letter stimuli in whole report tasks may influence the estimate of VSTM capacity due to contribution from verbal short term memory (Vogel, Woodman, & Luck, 2001; Olsson & Poom, 2005). We do suggest that the bilateral field advantage in VSTM and visual processing capacities may be domain-specific, however, further research is needed in order to determine which visual domains benefit from bilateral target presentations. The use of a change detection task, for example the unforced version of a two-alternative change detection paradigm developed by Kyllingsbæk and Bundesen (2009), will allow testing VSTM capacity variations for unilateral and bilateral displays for visual domains beyond letter recognition.

4.3. Limitations of the study and perspectives

As stated in the previous section, future studies are needed to determine under which circumstances a bilateral field advantage can be obtained for distinct visual attention capacity parameters and under which circumstances the effect varies in size. Our data shows that a bilateral field advantage for the parameters of both visual processing capacity and VSTM capacity can be observed for a letter identification task at a fixed target eccentricity and fixed target spacing. Future studies should test whether the bilateral field advantage increases if task difficulty increases, e.g., by introducing distractors. Furthermore, it should be investigated whether the bilateral field advantage is restricted to specific visual modalities by changing the stimulus material (e.g., color task). In addition, we tested the unilateral and bilateral conditions in separate blocks. A future study should test whether the bilateral field advantage can be replicated in a mixed design, varying unilateral and bilateral presentations randomly from trial to trial. Finally, we must determine whether unilateral and bilateral differences in visual attention capacity parameters vary across the visual field (e.g., with parafoveal vs. peripheral stimuli and with target spacing).

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