Distance versus hemifield costs in the identification of cued double targets[1]

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The paradigm of *cued visual selection* was used to measure the identification speed of single targets and target pairs in large item arrays. Four target categories were tested: oblique lines (*orientation,* Exp.1 and 5a), vertical bars with the upper and lower halves slightly displaced (*Vernier's,* Exp.2), T letters at four orientations (*T's*, Exp.3), and red or green oblique lines (*conjunctions,* Exp.4 and 5). In all experiments, performance with double targets in various distances from another was compared with that for single targets at the same presentation time. Despite reported differences in the need of attention for their discrimination, all four target types revealed similar performance characteristics in the task. The identification of double targets was strongly disturbed at near target distances (2.5 deg), slightly disturbed at medium distances (6.5 deg), and not or only little disturbed at far target distances (12 deg). Also the identification of individual targets in target pairs was usually worse than that of single targets, except at far distances. In later analysis, target pairs were also distinguished whether they had been located in same or different visual hemifields. It turned out that all near target pairs were located in same, all far target pairs in different hemifields. To disentangle hemifield from distance variations, a new set of target positions was tested (Exp.5), in which near and far distances occurred both within and across hemifields. The results revealed a clear predominance of hemifield effects. The identification of target pairs presented in *same* hemifields was notably worse than the identification of target pairs presented in *different* hemifields. Distance variations had almost no effect. In an aside finding, the study collected further evidence for an independent feature processing in conjunctions; the color of colored lines was always faster identified than their orientation (Exp.4). This questions the need of attentional binding processes in the identification of certain conjunction targets.

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INTRODUCTION

The role of cued focal attention has a long history in vision research. About fifty years ago, Eriksen and coworkers (Eriksen & Colegate, 1971; Eriksen & Hoffman, 1972, 1973) showed that targets could be faster identified when their locations were marked before the stimulus occurred. They described their observations by *selective attention*. The findings were elaborated in numerous studies during the following years. Posner and colleagues, for example, showed that even a *single* target was faster responded to when its location was previously indicated ("cued") than when it was not or incorrectly cued (e.g., Posner, 1980; Posner & Cohen, 1984). Cuing was obtained in different ways, either indirectly by a distant symbolic pointer (endogenous cuing) or directly by a small visual stimulus at the target location (exogenous cuing); the obtained effects differed in several aspects including

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[1] This paper is longer than papers I would like to read -- apologies. But I wanted to show the data from all experiments to underline the similarities and differences with different target types. The format of presentation is similar between experiments, and subheadings may help you to select (or skip) sections you are particularly interested in (or not).

spatial and dynamic properties (Jonides, 1981; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Yantis & Jonides, 1990; Cheal & Lyon, 1994; Turatto *et al.*, 2000; Chakravarthi & VanRullen, 2011).

Another major line of vision research in those days was visual search. Seminal studies reported that, in large ensembles of visual items, certain items were found immediately while others required careful and time consuming inspection of several items until the target was found (Treisman & Gelade, 1980; Treisman, 1985; for an overview, see Wolfe, 1998). Although numerous studies were performed to study the influence of focal attention on target identification, it took the vision community quite a while to connect both lines of research, cuing and visual search (but see, e.g., Nakayama &Mackeben, 1989; Wolfe, Cave & Franzel, 1989; Wolfe, 1994). Meanwhile there seems to be a wide agreement that it is not primarily specific features which lets some targets being faster detected than others but associated variations in salience, a kind of cuing, that may attract and guide attention to the according target locations and thus help to find, select and identify these targets (Cheal & Lyon, 1994; Gao, Mahadevan, & Vasconcelos, 2008; Kamkar, Moghaddam, & Lashgari, 2018).

Studies from my lab have contributed to these findings (e.g., Nothdurft, 1991, 1992). After I could show that search dynamics are largely independent of the explicit type of cuing ─ fast search is similarly obtained from local feature contrast and from a small cue surrounding the target (Nothdurft, 2002) ─ I mainly concentrated on the dynamics of the cued selection process itself. In a number of studies I confirmed the critical role of the cue size for the speed of target identification (Nothdurft, 2016; see Eriksen & St. James, 1986; Benso, Turatto, Mascetti, & Umiltá, 1998) and measured the strength of underlying neural signals (Nothdurft, 2017a), ocular variations in binocular rivalry (Nothdurft, 2018a) and temporal differences in the perception of cues and various target properties (Nothdurft, 2018b). The present study is from a different line of research performed at the beginning of these studies; it looked at the cuing of more than one target at the same time.

It has always been an interesting and challenging question whether the "spotlight" of focal attention can simultaneously be directed to different locations in a scene and, if so, whether attention would then be split into different "beams" or basically remain compact (e.g., Eriksen & Yeh, 1985). Thus, when two distant targets in a scene are simultaneously detected and identified, is that provided by two separate processes working in parallel, or by a single process working over a larger area covering both targets? While some observations suggested that attention may indeed be spatially split, perhaps on a feature-based level (Bichot, Cave, & Pashler, 1999; Itthipuripat, Garcia, & Serences, 2013; Jefferies & Di Lollo, 2015), other studies reported that this split might be transient only and disappear quickly, leaving a merely continuous distribution of attention in the visual field (Dubois, Hamker, & VanRullen, 2009). An interesting generalization came from the question of how many different targets can be monitored in parallel, that is, to how many targets can we simultaneously attend when they are moving around (Pylyshyn & Storm, 1988; Pylyshyn, 1989). The "magic" number from these studies seems to be four (but see Alvarez & Franconeri, 2007; Franconeri, Alvarez, & Enns, 2007; de-Wit, Cole, Kentridge, & Milner, 2011) but larger numbers may be reached when targets are perceptually grouped (Yantis, 1992) and, instead of individual targets, larger target configurations are monitored (Merkel, Hopf, & Schoenfeld, 2017). Even the seemingly parallel processing of four targets, however, is apparently obtained from fast attention switches between targets (Holcombe & Chen, 2013; cf. Alvarez & Franconeri, 2007). All models of shared visual attention predict that a single target should be better and faster identified than pairs of simultaneously presented targets.

Cued visual selection as tested in my experiments includes different steps of processing. First, one (or more) targets must be *selected* and, second, each target must be *identified* (Sagi & Julesz, 1985); these two processes are performed at different speeds (Sagi & Julesz, 1985; Scialfa & Joffe, 1995; Nothdurft, 2000, 2002, 2006) and are differently affected by attention and resource limitations (Braun & Sagi, 1990; Braun & Julesz, 1998). Target selection is achieved in parallel (Sagi & Julesz, 1985; Nothdurft,1992) and likely not limited by the number of cued objects. In a strictly serial search task with colored lines, search time could be either related to the number of items shown or to the number of *cued* items in a larger pattern, suggesting that observers had an immediate overview of all cued items in the set (Nothdurft, 2006).

For the *identification* of multiple targets, however, numerous restrictions have been reported. It is generally not possible to identify "difficult" targets simultaneously (e.g., Braun & Julesz, 1998); in fact, the attentional demands of a target identification task were explicitly measured by performance reductions obtained under a simultaneous letter discrimination task (Braun & Julesz, 1998; see also Braun & Sagi, 1990). But not all targets seem to require attention for their identification. The discrimination of simple target features (like orthogonal lines), for example, was reported to be less disturbed by withdrawing attention than the discrimination of T's and L's (Braun & Julesz, 1998). But even with simple oriented lines is target identification accompanied by attention shifts to the target (Joseph & Optican, 1996; Nothdurft, 1999). A useful synopsis of these findings thus seems to be that the discrimination (and identification) of targets *does* require directed attention but that not all targets need the *same amount* of it to become correctly identified. Simple targets may require less exclusive attention than complex targets like T's and L's, Vernier's, and certain feature combinations (Treisman & Gelade, 1980, but see Braun & Julesz, 1998). A general exception seems to be color which is apparently identified even when attention is absorbed in a different task (Braun & Julesz, 1998; see also Nothdurft, 2020).

The experiments reported here were performed on this background almost 20 years ago. Using the technique of (exogenously) cued visual selection, the experiments were designed to measure potential benefit and cost effects when cuing (and identifying) two targets instead of only one. Is the identification of two targets achieved independently of each other, or is it improved or deteriorated compared to the identification of one target alone? Do benefit and cost effects vary with the distance between targets? Since then, however, several new findings have been reported in the field. The limited spatial resolution of focal attention at different eccentricities (Intriligator & Cavanagh, 2001; see also Sagi & Julesz, 1986) would predict that it may be impossible to attend independently to different targets in too close configuration. Of particular importance, however, were observations that the tracking of multiple objects turned out to be easier when targets were presented in different than in same visual hemifields (Alvarez & Cavanagh, 2005; Alvarez, Gill, & Cavanagh, 2012; Holcombe, Chen, & Howe, 2014). All these new observations were also seen in the experiments presented here. The identification of cued target pairs was strongly deteriorated when targets were presented too close together; these interactions disappeared when target spacing was increased and targets were presented in different hemifields. This was equally found for simple and complex targets.

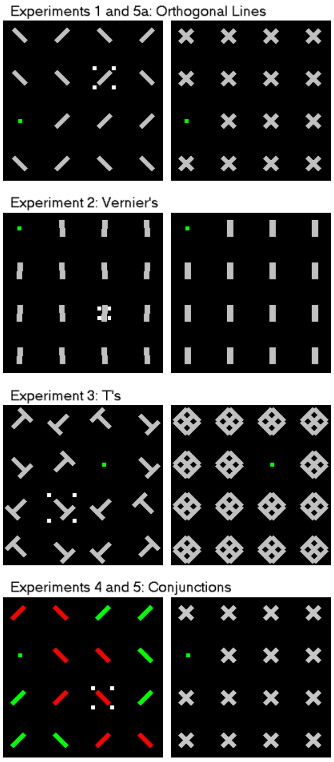


Figure 1. *Test pattern examples.* Full patterns displayed 80 items and a central fixation point (green); the examples here show only sections. Four-dot cues indicated which item(s) had to be identified (left-hand patterns); after a given presentation time all items were masked (right-hand patterns).

METHODS

Overview

Experiments were designed to measure the identification rates of single targets and compare it with that of double targets at various distances from each other. In different series of experiments, four target types were tested (Fig.1): orthogonally oriented oblique lines, lines with very small orientation differences (effectively Vernier's), oblique T's at different orientations, and conjunctions of color and orientation. In large patterns with 80 items one or two items were cued (thus becoming the *targets* in this trial) and had to be identified by the observer. Presentation time after the cue was varied and performance accuracy was measured as a function of presentation time after the cue. Performance in identifying two simultaneously cued targets was compared with predictions based on the identification rates of single targets at the same presentation time.

Stimuli

Stimuli were generated with DOS VGA techniques on a 15" ultra-high resolution monitor (Ergo-View 15; Sigma Designs Inc., Fremont, California) 67 cm in front of the observer. Repetition rate was 100 Hz. Observers had their heads conveniently leaned against the wall; head size differences resulted in small distance variations (±1.5 cm) between the observers' eyes and the monitor.

Test patterns displayed regular arrays of 80 similar items in a 9 x 9 rectangular raster (raster width 1.8 deg); the center element of the raster was spared and a green fixation marker (0.2 deg x 0.2 deg) was shown instead. Full patterns covered an area of approximately 15 deg x 15 deg. Four target categories (Fig.1) were tested in different experiments; (a) *orthogonal oblique lines* (± 45º; 0.8 deg x 0.2 deg); (b) slightly tilted lines (± 6º; 0.7 deg x 0.24 deg), which were effectively *Vernier's* with the upper and lower halves slightly displaced (2' = 0.034 deg); (c) *T* letters at various oblique orientations, 0.8 deg x 0.9 deg); and (d) colored lines *(conjunctions)* of the same size as in (a) in red or green color; colors were matched in luminance, individually for each observer, using heterochromatic flicker photometry. All items in a pattern were simultaneously switched on; 100 ms later, one or two of the items were briefly cued (20 ms). After a variable presentation time all items were masked. *Masks* represented a combination of possible target stimuli in each test and were always white, even for colored test patterns.

Cues were made of four little squares (0.2 deg x 0.2 deg) placed at different distances around each target in the four oblique directions. With oblique lines (a and d), the distance was 0.6 deg, with Vernier's (b) 0.3 deg, and with T's (c) 0.8 deg from the target center. The different distances generated cues of slightly different size (0.6-1.6 deg in diameter); the variations were introduced to optimize cue efficiency and simultaneously avoid an overlap of cue and test items that might have reduced target visibility (Nothdurft, 2016). Examples of test patterns with cues and masks are shown in Figure 1.

To reduce performance variations from crowding (Nothdurft, 2017a) and limited attentional resolution (Intriligator & Cavanagh, 2001) but still keep the uncertainty of cued locations large enough, possible *target locations* were restricted to certain raster positions. Subjects were not informed about these restrains. Beside different conditions for single targets, target pairs were generally presented at three different distances to each other (Fig.2), here described by the absolute raster distance in columns and rows, $d = (|\Delta x|, |\Delta y|)$. For NEAR target distance, $d = (1,1)$, the two targets were placed in adjacent rows and columns. For MIDDLE distance, $d = (3,2)$, targets were placed three columns and two rows apart. For FAR distance, $d = (6,3)$, the column distance was 6 and the row distance 3. Different but individually comparable restrictions of target locations were used in these conditions (Fig.3). For single targets and target pairs with NEAR or MIDDLE target distances, one target location was randomly chosen from an area extending

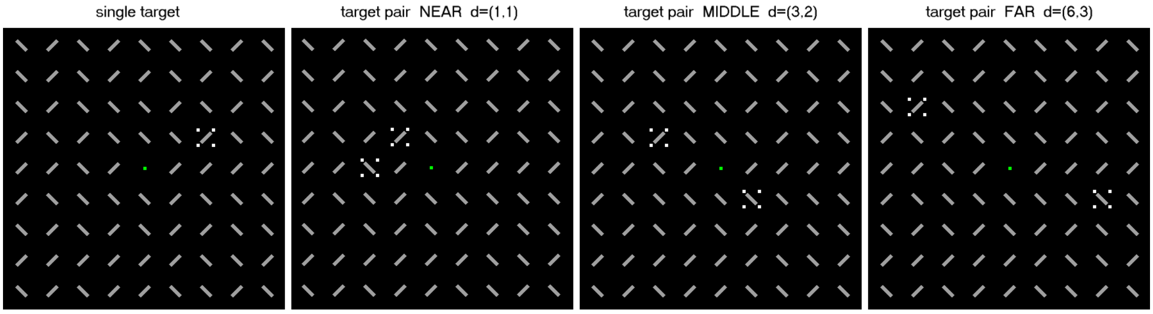
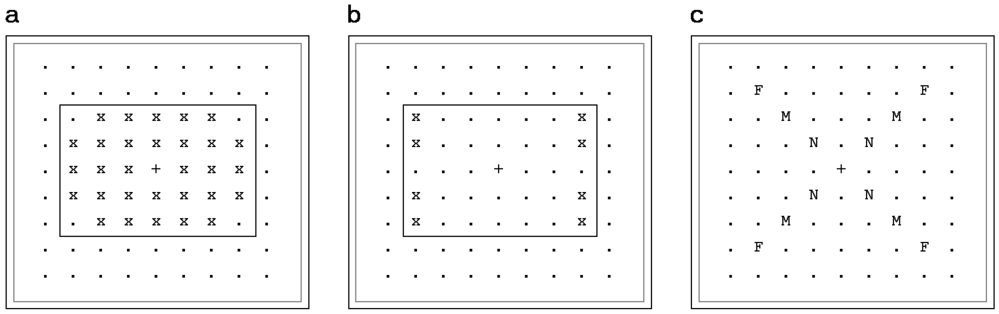


Figure 2. *Examples of single and double line targets at various distances (Exp.1).* Observers fixated the central fixation point. Shortly (100 ms) after stimulus onset, one or two targets were cued (20 ms). After presentation time (typically 10-150 ms) all lines were masked (Fig.1). Observers reported the cued target orientation(s) from left to right. Note that the relative target spacings were fixed but could vary in the absolute locations on the screen.



Experiments 1-4
singles, NEAR, and MIDDLE
NEAR dist=(1,1), MIDDLE dist=(3,2)
+ fixation point

Experiments 1-4
singles FAR, FAR dist=(6,3)
+ fixation point

Experiments 5 and 5a
N=NEAR, M=MIDDLE, F=FAR
+ fixation point

Figure 3. *Possible target locations in raster patterns.* **a.** NEAR, MIDDLE, and **b.** FAR distance conditions in Experiments 1-4; **c.** target locations in Experiments 5 and 5a. In *(a)* and *(b),* the *x's* indicate possible target locations. For target pairs, the second target was randomly located at the distance to be tested; if it happened to fall outside the indicated area (rectangles), a new target location was selected and the procedure repeated. In *(c)*, single and double targets in different distance conditions were placed at fixed locations.

horizontally to about 5.5 deg on either side of the fixation point, and vertically to 3.6 deg above and below (Fig.3a). For the second target (if required) a location at the required distance was chosen, randomly to the left or right, above or below the first target; if that location happened to fall outside the allowed target area (rectangular outlines in Fig.3a and b), the selection process was repeated. This algorithm was modified for FAR target distances (Fig.3b). The location of single targets or the first target of a FAR target pair was restricted to eight raster positions in the periphery; the second target (if required) was then located six columns apart on the other side of the pattern randomly above or below the row of the first target. Again, if that location happened to fall outside the allowed target area, the selection process was repeated. As a result of this procedure, target pairs in FAR distance were generally located farther in the periphery than target pairs with NEAR or MIDDLE distances. Performance in these conditions was therefore compared with performance in the according single targets tests. For Experiments 5 and 5a, a new algorithm for target locations was used, in which targets occurred at selected locations (Fig.3c) which could be combined with other targets at the same eccentricity in either same or different hemifields. NEAR, MIDDLE, and FAR target distances were then represented by slightly differed target spacings than in Experiments 1-4. Performance in target pair conditions was always compared with that of single targets at the same eccentricity. NEAR, MIDDLE, and FAR conditions were intermingled in the test runs; therefore, the overall variation of target locations in a run still was high.

All stimuli except the fixation marker (green) and the items in Experiments 4 and 5 (red or green) were white on dark background. *Luminance settings* were 15 cd/m² for items and masks, and 78 cd/m² for cues. Red and green stimuli in Experiments 4 and 5 were slightly brighter (about 27 cd/m²) and were individually matched for luminance. The fixation marker had about 50 cd/m². Note however that all luminance measures were taken with larger stimuli which appeared much brighter on the screen than the small blobs of cues and the fixation point. All stimuli were presented on a dark background (3.5 cd/m²).

Procedures

Stimuli were binocularly viewed. Trials started with a 1s presentation of the fixation marker before the test pattern occurred. At 100 ms delay, one or two four-dot cues were superimposed on the pattern for 20 ms. After variable presentation time (measured from the cue onset), all items in the pattern were masked for 500 ms. Thereafter, the screen was blanked and only the fixation point remained visible. Subjects could enter their responses without any time pressure. After a short blank of the entire pattern, a new trial began with the presentation of the fixation point.

Responses were made in modified two or four alternative forced-choice tasks by pressing certain keys on a computer keyboard. The modifications were that subjects could (i) reject, and later repeat, a trial if they felt they had been inattentive or distracted during the presentation, and (ii) cancel their last response immediately after the trial if they noticed they had pressed the wrong key(s). For single targets, only one response had to be made; for target pairs, two responses had to be made in sequence beginning with the left-most target and then the other target more towards the right. Due to the target configurations used in Experiments 1-4, targets could never occur in the same column. In Experiment 5, however, target pairs could appear in same rows or columns (Fig.2c). For pairs located in the same column, the response to the upper target had to be entered first, then the response to the lower target. Observers quickly learned these response sequences, and always had enough time to mentally sort their target percepts before responding. Different keyboard keys were used for targets in Experiments 1-5. For oriented lines and Vernier's (Exp.1, 5a, and 2), response keys were linked to the according percepts (left-hand “<” key for targets tilted to the left; right-hand “-” key for targets tilted to the right; German keyboard layout). This selection was modified for the red and green tilted lines in Experiments 4 and 5. Red targets were entered with two left-hand keys, green targets with two right-hand keys; in either hand, the key more towards the left was associated with line tilts to the left ("<" and ".", for red and green lines, respectively) and that more towards the right with right-tilted lines ("y" and "-"). For T's at different orientations (Exp.3), four keys of the numeric keyboard pad on the right-hand side of the keyboard were used to enter the according letter orientation ("4" and "5" for upright T's tilted to the left and right, respectively; "1" and "2" for T's upside-down tilted to the left and right). After one or two short introduction runs, all observers had become familiar with the tasks and the keys to use.

Throughout experiments, *tests were blocked* for target types (lines, Vernier's, T's, conjunctions) and in Experiments 1-4 also for the tested target distances (NEAR and MIDDLE vs. FAR). In Experiments 5 and 5a, all target distances and according single target locations were tested in one run. In the first run of each experiment, appropriate ranges of target durations were coarsely estimated; thereafter, each run included up to 10 fixed durations of single and paired test conditions in random sequence with 5-10 repetitions each. A typical run in Experiment 5 thus covered more than 60 different target conditions (e.g., 7 durations each tested with 3 target pairs within, 3 target pairs across hemifields and 3 according single target conditions), which resulted in a total run with >300 (5 repetitions) to >600 test trials (10 repetitions of each condition). Since distance variations were split in Experiments 1-4, there were always two runs, one with up to 30 test conditions (7-10 durations tested with one single and two target pair conditions, NEAR and MIDDLE) and one with up to 20 test conditions (up to 10 durations with FAR distance pairs and the according single target conditions). Targets at FAR distance were often more difficult to identify and required longer presentation times for high accuracy; therefore, the range of tested target durations was sometimes increased for FAR conditions. Each run was repeated several times by each observer to obtain the averaged performance accuracy in sometimes 60, usually 100 repeated tests. NEAR/MIDDLE and FAR distance runs in Experiments 1-4 were tested in alternation to minimize differences from eventual long-term training effects. Experiment 5 was later added to the series of experiments. All data were collected in sessions of 2h, during which subjects could pause when necessary.

In all tasks of the study, observers were asked to fixate a central *fixation marker*; good fixation performance was initially controlled and repeatedly checked with a video camera focused upon the observer's eyes. In most runs, target presentation times were anyhow too short to gain advantages from directed gaze shifts to the cues.

Analysis

After completion of a test series, the accuracy data in different conditions were compared. In particular, the expected performance with target pairs was predicted from the measured performance with single targets as the combined probability of identifying two independent single targets, target 1 and target 2 (t_1 *and* t_2),

$p_{pred}\,(t_1 + t_2) = p_{pred}\,(t_1 \cap t_2) = p\,(t_1) \cdot p\,(t_2)$.

Since the two targets virtually produced the same identification rates, $p\,(t_1) = p\,(t_2) = p\,(\textit{single target})$, predictions were obtained from squaring the single target identification rates, $p_{pred}\,(\textit{target pair}) = p^2\,(\textit{single target})$. Predictions were compared with the measured identification rates for target pairs at the same presentation times. Deviations of measured data from predictions, $\Delta = p_{pred} - p_{measured}$, should then reveal cost ($\Delta > 0$) or benefit effects ($\Delta < 0$) of double target identifications compared to that of single targets, for a given target distance and presentation time. Analysis did also look at preferences for one or the other target in target pair conditions.

Subjects

Four observers (two female, two male) participated in the study. Three (age 20-34 years) were university students and were paid for the time they spent in the experiments. The fourth observer was the author (54 years). Subjects had normal or corrected-to normal visual acuity on both eyes and, except the author, were naive about the aim of the experiments. All subjects had carried out other experiments with cued target identification before.

RESULTS

The study reports five series of experiments with four different target types (Fig.1). The test sequence was not the same in all observers and is here sorted for the clarity of presentation. Experiment 1 (oriented lines) tested performance with relatively simple target features and is here also used to introduce the major steps of analysis. Experiments 2 (Vernier's) and 3 (T's) present data obtained with more complicated targets which are commonly reported to require focal attention for identification and discrimination. Experiments 4 and 5 (conjunctions) transfer the task to targets with feature combinations of orientation and color, and also add a final test with new target locations which allowed for a better distinction of distance and hemifield effects.

Experiment 1: Orthogonal oblique lines

Accuracy variations with single targets. When in an array of randomly oriented oblique lines one line is cued (Fig.1), observers can quickly identify it and report its orientation. With optimal delays between the stimulus and cue onsets, the needed presentation time for high performance rates can be rather short, with notable variations between observers (Nothdurft, 2002, 2017a, 2019). Also in the present study, the speed of target identification varied between subjects (Fig.4). One observer (red symbols) reached perfect target identification with much shorter presentation times than the other observers (including the author). With longer presentation times their performance also increased and finally all observers reached an identification rate of 1 or almost 1 (i.e., 100% correct). Target identification was generally faster with targets in NEAR and MIDDLE conditions than with targets in the FAR condition, where all targets were presented at an increased eccentricity (Fig.3b). Similar performance variations between observers were seen in all experiments of this study and reflect individual differences in the speed of attention shifts and target discrimination. For a first overview of systematic performance variations these individual differences were ignored and instead the mean responses (and s.e.m.) were calculated (black symbols). In the detailed comparisons of target conditions, however, the individual responses of each observer were analyzed.

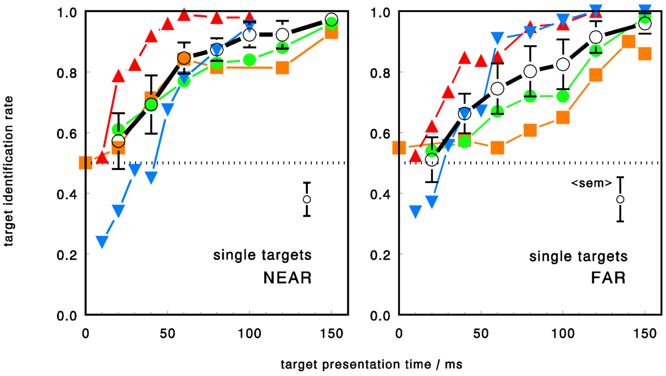


Figure 4. *Individual performance variations with single targets in Experiment 1;* four observers (colored curves). One observer (red) identified the targets particularly fast. For an overview of experiments, the identification rates of all observers were averaged (black symbols; errors bars indicate the s.e.m.); missing data points for single observers were interpolated. For detailed analysis, the individual data of each observer, at same presentation times, were compared between conditions. In this and following figures, also the mean s.e.m. ("<sem>") of averaged data is shown.

Performance variations with target pairs. How do observers perform if instead of one single target two targets are cued and must be identified? The mean performance ratings of all four subjects to target pairs in NEAR, MIDDLE, or FAR distances are shown in Figure 5, together with the mean responses to single targets. At all distances, the accuracy of target pair ratings (orange) was far below that of single lines (black). This is not surprising, however. If limited perceptual resources must be shared among two targets instead of one, the rate of correctly identified target pairs should be smaller than that of correctly identified single targets. The expected rate for double targets can be predicted as the combined probability of identifying two independent single targets (which is obtained by squaring the identification rate for a single target). These rates are plotted as gray continuous curves in Figure 5 and lie below the identification rates for

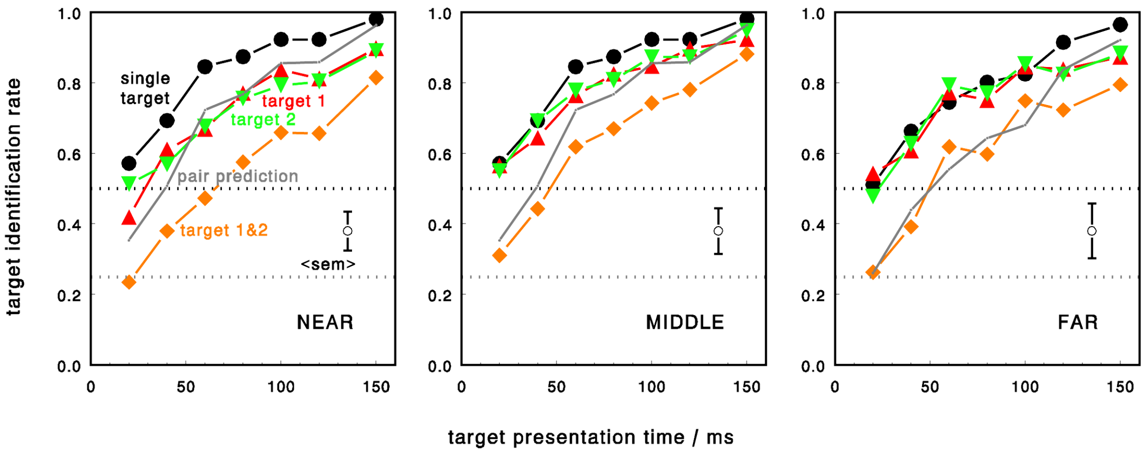


Figure 5. *Mean performance in Experiment 1 (oriented lines).* Graphs plot target identification against presentation time for the three tested distance conditions of target pairs. From the performance with single targets (black; identical for NEAR and MIDDLE conditions) predictions for the simultaneous identification of two independent targets were made (gray). These are compared with the measured identification rates of target pairs (orange) and individual targets in pair conditions (red and green). Target 1 is the left-most target, target 2 the right-most target on the screen. Chance levels for single targets and target pairs differ (black and gray dotted lines, respectively). The single data point with error bars gives the mean s.e.m. of all averages in the graph. Target pair ratings lay far below predictions, except in the FAR condition. Individual targets in pair conditions were identified equally well but less accurately than single targets, except in the FAR condition.

single targets. Interestingly, the *measured* identification rates for target pairs in NEAR and MIDDLE distances were even below these curves; only for FAR target pairs did the gray and orange curves partly overlap. Altogether, Figure 5 shows that the identification of double targets is strongly deteriorated for targets in NEAR distance, less so for targets with MIDDLE distance, and only little for targets in FAR distance from each other.

Accordingly, the identification rates of either target in pair configurations (red and green curves in Fig.5) were also reduced at certain distances, compared to the identification rates of single targets. This is quite obvious in the NEAR distance condition, where the identification rates for individual targets in pair conditions were often as low as to be expected for target pairs. The reduction was smaller in MIDDLE distance conditions and almost absent with FAR distances (except at durations longer than 100 ms). Here, the identification rates for the individual targets in pair conditions were often the same as those for single targets, suggesting that the target selection and identification were only little affected by the number of cued lines. The correct identification of *both* targets together, however, was still deteriorated and close to the values predicted from combined ratings (orange and gray curves).

No difference between targets. Another interesting observation in Figure 5 is the equal accuracy at which observers identified the two targets in paired target conditions (red and green curves). Remember that observers had to enter their responses in sequence beginning with the left-hand target and then the target more towards the right. That might have biased them to concentrate more on the left-hand than on the right-hand target. In fact, however, the two ratings are nearly identical in Figure 5, indicating that observers had distributed their perceptual resources equally to both targets. This is also seen in the individual identification rates from all target pairs in various test conditions. The scatter data in Figure 6 (left-hand and right-hand targets are here and in the following named targets 1 and 2, respectively) show no systematic bias and a negligible deviation from midline (mean accuracy difference *target 1 – target 2* = -0.001 ±0.007). Thus, there was no systematic preference for one or the other target in Experiment 1.

Analysis of target distances. The observations with different target distances in Figure 5 are also analyzed on the basis of individual data (Fig.7). For the scatter plot in Figure 7a, all *predicted* ratings from each observer (abscissa) are compared with the according *measured* identification rates (ordinate) in the same condition and for the same presentation time. The graph shows a strong shift of data points from the midline towards the lower right-hand side; that is, measured accuracies were, on average, notably smaller than the accuracies predicted for two independent single targets (mean difference *predicted – measured ratings* = 0.081 ±0.012, corresponding to a mean difference of 8.1%). Altogether this bias indicates that targets in double target conditions were not analyzed independently of each other but did severely interact.

The starting question of this study was to measure if this interaction varied with the distance between targets. Thus it should be interesting to see if interactions, i.e. the deviations in Figure 7a, varied with the different target distances tested. This analysis is shown in the remaining graphs of Figure 7, using cumulative distribution plots of the deviations in Figure 7a. Deviations were calculated as the difference between predicted and measured data; they were positive if the measured accuracy was smaller than predicted, and negative if it was larger. Positive deviations thus indicate a *suppression* or *deterioration* of target pair identification beyond the effects of combined probabilities. Cumulative distributions plot the growing number of such events in the data sample with increasing deviation values. (Basically, the curves reflect the cumulated counts (ordinate) of deviation data in Figure 7a while passing through the graph, perpendicular to midline, from the upper left to the lower right (abscissa); deviations at high or low ratings are not distinguished.) Overall, the deviations were strongest for target pairs in the NEAR target distance (Fig.7b, red) and smallest for pairs in FAR distance (blue curve), as was already seen in the mean data of Figure 5. In Figure 7b (and all corresponding curves in the following figures) also the *mean* deviations are indicated for each curve. They are always close to the median (curve intersections at cumulative distribution level 0.5; dotted lines) indicating the absence of major outliers in the data. These mean deviations will be used in the summarized analysis below.

Analysis of target locations within or across visual hemifields. During analysis, an interesting new question came up, whether there was a difference between target pairs presented in *same* and *different* visual hemifields. For that, all tested target pairs were evaluated whether the targets were both located on the same side of the visual field or on different sides. Targets located in the central column above or below the fixation point were taken as falling into the same hemifield as the other target. With this rule it became obvious that targets at NEAR distance, *d* = (1,1), were always located in the same visual hemifield and targets at FAR distance, *d* = (6,3), always in different hemifields; otherwise these distances could not be realized. Only for targets in MIDDLE distance, *d* = (3,2), could targets fall either into the same or different hemifields. But even with targets in same hemifields, one target had to be located in the central raster column (see Fig.3). When data from the MIDDLE distance were accordingly sorted and distinguished, cumulative distribution curves show a small shift between conditions (Fig.7c); target pairs in different hemifields produced, on average, smaller deviations than target pairs in same hemifields. Together with the data samples from NEAR (all pairs within same hemifields) and FAR target distances (all pairs in different hemifields), the overall data for conditions in *same* or *different* visual hemifields can be summarized (Fig.7d). Deviations were larger for target pairs within than across the two hemifields.

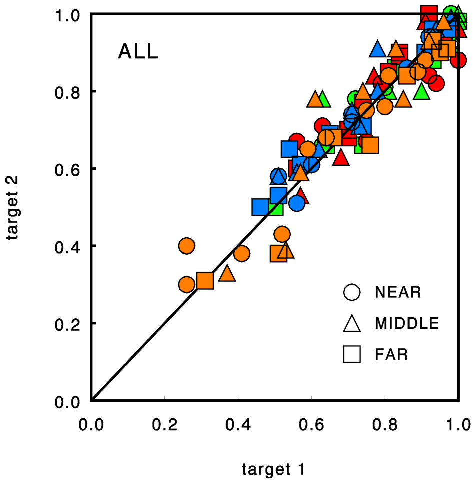


Figure 6. *Scatter plot of target 1 vs. target 2 identifications in Experiment 1.* All data pairs from individual observers (color-coded); distance conditions are indicated by symbols. In all conditions and over all observers, the left-hand (target 1) and right-hand targets (target 2) of a trial were equally seen and identified. Two outliers removed.

The mean deviations from Figure 7b-d are replotted in Figure 8a. Without the hemifield distinction (red, green, and blue data points, black curve), there is a strong decay from NEAR (mean deviation 0.141 ±0.022) over MIDDLE to FAR target distances (0.039 ±0.016). Thus, target interactions (large deviations) were strongest in NEAR (red), and smallest in FAR distance conditions

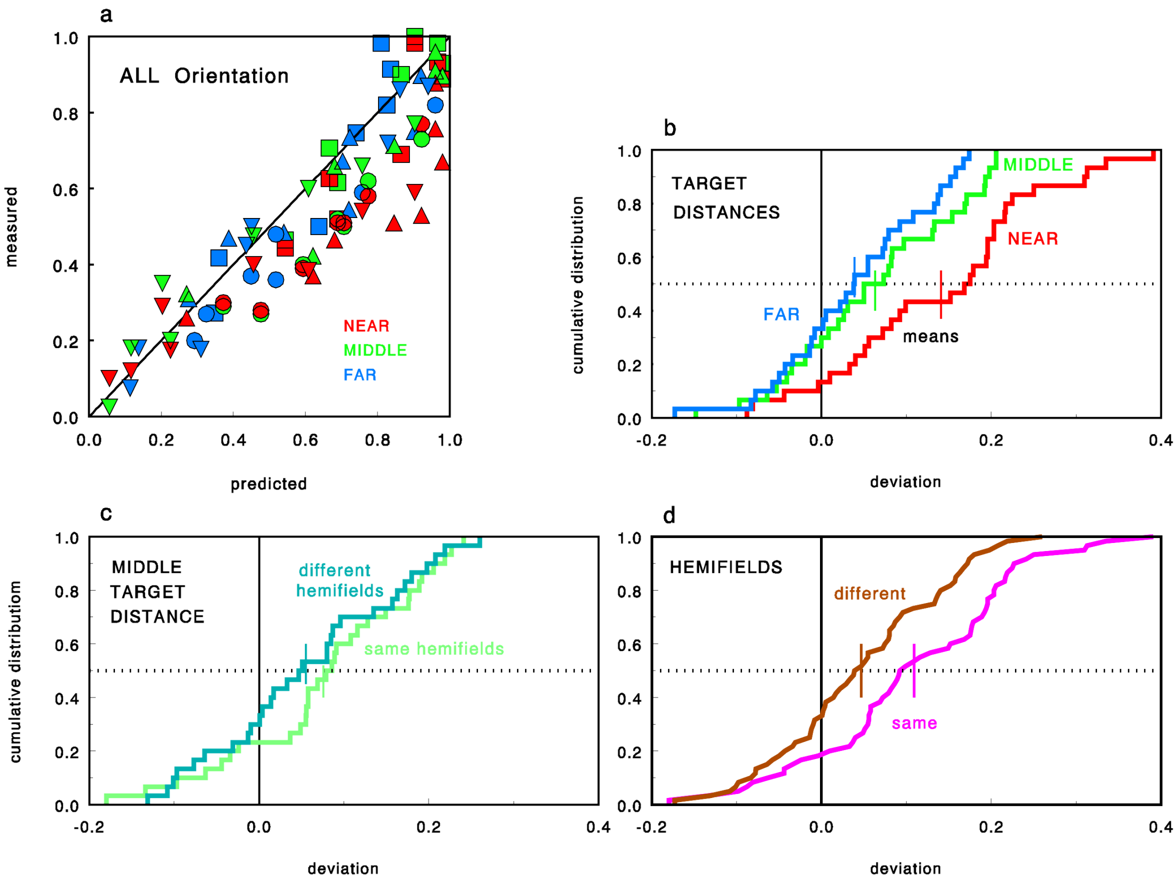


Figure 7. *Performance with target pairs in Experiment 1.* **a.** Deviations of measured from predicted target identifications; data from all observers (different symbols; distance conditions are color-coded). **b.-d.** Accumulated deviation distributions for different conditions in *(a)*. With growing values (corresponding to moving perpendicular to the identity line in *(a))*, curves show the increasing frequency of deviations at or below the current value. Means are indicated; medians are the values at 0.5 (dotted lines). *(b)* Differences between distance conditions; the mean deviation for NEAR target pairs is largest, that for FAR target pairs is closer to zero. In *(c)* and *(d)* target pairs were distinguished whether they were located in *same* or *different* visual hemifields. A direct distinction could only be made for targets in MIDDLE distance conditions *(c)*. NEAR target pairs were always localized in *same*, FAR target pairs always in *different* hemifields. *(d)* Accumulation of deviations from all target pairs in *same* and all target pairs in *different* hemifields. Overall, the deviations of measured from predicted identification data (performance "costs" with double targets) were largest in NEAR target distances and for target locations within same visual hemifields.

(blue). The hemifield distinction (which could only be made with targets in MIDDLE distance) shifted the curve slightly above or below the original mean deviation value (bright green and cyan data points). In the overall sample of target combinations in same or different visual hemifields, irrespective of their distance to each other (Fig.7d), mean deviations reveal an average biased towards the most prominent conditions NEAR and FAR (magenta and brown dashed lines). Thus, the detection of target pairs of oriented lines was apparently modulated by two parameters; the spacing of targets and their locations in same or different hemifields.

The fact that NEAR and FAR target distances in Experiment 1 did not allow for a distinction of target locations in same vs. different hemifields was a pity for the hemifield analysis and has finally led to a modification of tested target locations in a new experiment (Exp.5) on conjunction targets. A similar modification (Exp.5a) was also tested with *white* oriented lines as used in Experiment 1 (see below). The data (Fig.8b) strengthen

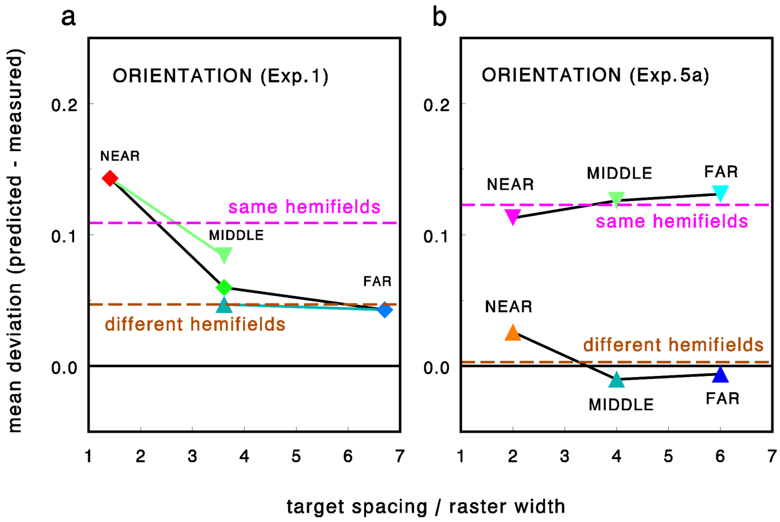


Figure 8. *Distance and hemifield effects in Experiments 1 and 5a.* **a.** Mean deviations (as in Fig.7b-d) are summarized for pair conditions tested. In Experiments 1-4, NEAR target pairs were always located in *same*, and FAR target pairs in *different* visual hemifields. **b.** Only in Experiments 5 and 5a, distance and hemifield variations could be distinguished. Colors of data symbols and dashed lines correspond to the colors in Fig.7 and partly those in Fig.24.

the hemifield effect. For targets located in same hemifields, deviations were strong at all target distances; for targets located in different hemifields, even NEAR target spacings produced only small deviations. Altogether the data suggest that the identification of double targets was mainly independent (revealing *small* or absent deviations between predicted and measured performances) when targets were presented in different hemifields.

Statistics. The growing performance accuracy in the identification of cued orthogonal lines with increasing presentation time was already shown in a number of studies (e.g., Nothdurft, 2002, 2017a, 2019) and was also significant in the present data sample. The Mann-Whitney U-test revealed significant accuracy differences between the three shortest and the three longest presentation times from all observers (NEAR, $n_1 = n_2 = 12$, $U = 4$, $U_{krit} = 17$, $p < 0.001$; FAR, $n_1 = n_2 = 12$, $U = 1$, $U_{krit} = 17$, $p < 0.001$).

There was no significant difference between correct identifications of target 1 and target 2 in target pairs (Fig.6; Wilcoxon signed-rank test; $N = 95$, $|z| = 0.55$; note that for large N, the distribution approaches a normal distribution and test statistics can be accordingly transformed). An interesting observation was the seemingly similar performance with single targets and individual targets in certain target pairs (e.g., Fig.5, FAR). In the full data analysis (individual comparisons of all data pairs from all observers), single target ratings and individual target ratings in pair conditions were always significantly different, except for FAR target pairs (Wilcoxon signed-rank test; single vs. target 1, $N = 28$, $W = 129$, $W_{krit} = 116$, *n.s.*; single vs. target 2, $N = 30$, $W = 123$, $W_{krit} = 124$, $p < 0.05$, just about significant).

Deviations between predicted and measured accuracy data with target pairs (Fig.7) were significant in all subgroups tested, although at different significance levels (Wilcoxon signed-rank test, $N \geq 30$; NEAR, $|z| = 4.25$, $p < 0.0001$; MIDDLE, $|z| = 2.93$, $p < 0.005$; and FAR distances, $|z| = 2.21$, $p < 0.05$; *same* hemifields, $|z| = 5.34$, $p < 0.0001$; and *different* hemifields, $|z| = 3.29$, $p < 0.001$). The differences between deviations in distance conditions (NEAR; MIDDLE; FAR; Fig.7b) were significant (ANOVA; $F(2,87) = 8.05$, $p < 0.001$) and also between *same* and *different* hemifields conditions (Fig.7d; $F(1,118) = 9.56$, $p < 0.0025$) but not for the small subdivision of MIDDLE distance conditions (Fig.7c; $F = 0.56$).

Discussion. With oriented lines, the identification of double targets in NEAR or MIDDLE distances was worse than predicted for independent single targets. This indicates that either the processes of target selection or those of target identification were disturbed when targets were presented too closely together. The fact that the individual targets in target pairs at FAR distances could be identified as good as single targets (Fig.5 FAR; red, green, and black curves) suggests that not target *selection* but target *identification* might have been limited. (The possibility that target selection is affected by the distance is addressed in the General Discussion below.) Even at

FAR distances, however, double lines were not better identified than predicted from single line identification; thus, there was no facilitation from paired target cuing.

There have been inconsistent reports in the literature whether simple targets such as oblique lines do indeed require attention to be identified and distinguished. Sagi and Julesz (1985, 1986) claimed that orientation cannot be discriminated preattentively, but Braun and Julesz (1998) showed that the discrimination of "pop-out orientations" entails little if any attentional cost. But even popout orientations are associated with involuntary attention shifts to the target (Joseph & Optican, 1996; Nothdurft, 1999), their identification is facilitated by salient precues at the target's location (Theeuwes, Kramer, & Atchley, 1999; Nothdurft, 2002) and fails when attention is withdrawn from the target (Joseph, Chun, & Nakayama, 1997). There are no "attention-free" feature detectors for orientation (Inverso, Sun, Chubb, Wright, & Sperling, 2016), and also the strong interactions of NEAR but not FAR target pairs in Experiment 1, which both were similarly salient, suggest that the differences are not generated preattentively. All these observations indicate that even simple oriented lines in multiple line patterns require attention when they have to be identified. This makes them useful targets for studying the spatial and dynamic properties of attention (see, e.g., Nothdurft, 2017a).

Experiments 2 and 3: Vernier's and T's

To generalize the findings of Experiment 1, the task was repeated with more complex targets which are known to require spatial attention for their discrimination. Examples of such targets are the Vernier's and T's shown in Figure 1. Both targets require considerable effort for their identification and cannot be distinguished when attention is simultaneously distracted by a parallel discrimination task. The intention for using Vernier's was an original attempt to test a much smaller orientation difference of only a few degrees, but the limited resolution of the inbuilt VGA graphic card had deteriorated the (slightly) tilted lines to vertical lines in which the upper and lower halves were displaced (and therefore named *Vernier's*). Observers still performed the task by reporting the resulting tilt, similarly to the orientation task in Experiment 1. The reason for using T targets was their frequent use in the literature and the strong evidence that their discrimination requires focal attention being directed to the target (Kröse & Julesz, 1989; Braun & Julesz, 1998). Since both targets revealed similar characteristics (that however partly differed from the characteristics seen with oblique oriented lines in Experiment 1), the analysis and discussion of results are here combined, although the data are shown in separate figures in sequence (Figs.9-12 and Figs.12-15, respectively).

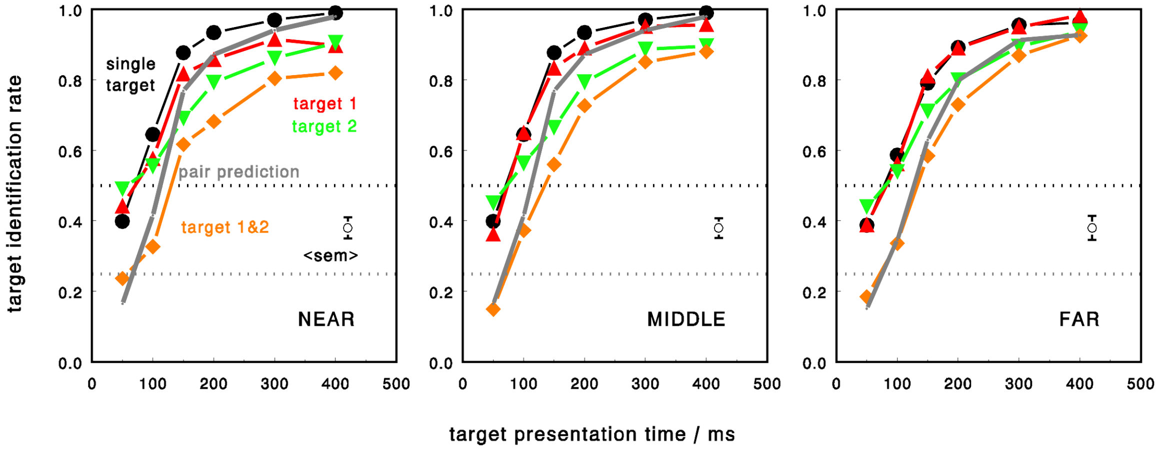


Figure 9. *Mean performance in Experiment 2 (Vernier's).* Presentation as in Fig.5. Vernier's required longer presentation times for identification than orthogonal lines before (note the different time scales to Fig.5). The identification of target 1 (red) was, on average, better than the identification of target 2 (green). Performance with target pairs was generally reduced even below the predictions from single targets, but was least reduced in FAR target conditions. Similarly, the identification of target 1 in target pairs was worse than that of single lines, but not in FAR conditions.

Target identification with single and double targets. The generally longer presentation times needed to distinguish these targets in comparison to orthogonally oriented lines is seen in several performance differences to Experiment 1. First, the accuracy in single target identification increases less quickly with increasing presentation time. In the means of all observers, Vernier's needed about 200 ms (Fig.9), and T's even 300 ms (Fig.13) to reach an accuracy level of 90% or more (ratings ≥ 0.9). In Experiment 1 this level was reached with oriented lines for target durations of about 100 ms (Fig.5). Interestingly, there was a similar ranking between observers; performance increased faster with some observers than with others, in both tasks. The second difference is the identification of targets 1 and 2 in target pairs. While the identification rates of target 1 (the left-hand target; red curves) and target 2 (the right-hand target; green curves) had been almost identical in Experiment 1 (Fig.5), there was a systematic difference in Experiments 2 and 3 (Fig.9 and 13). Left-hand targets (the properties of which had to be entered first) were identified more accurately (red) than the remaining right-hand targets (green). This indicates that target analysis was slightly biased for target 1.

Distance effects. In other aspects, performance variations with Vernier's and T's were similar to those with orthogonal lines in Experiment 1. Despite this bias of target 1 over target 2, for example, target 1 was generally less correctly identified than single targets except in the FAR target conditions where target 1 ratings closely overlapped the single target ratings (black vs. red curves in Fig. 9 and 13). This shows that target identification was severely deteriorated when targets were presented closely together; observers could not identify both targets together. Also similar to Experiment 1 is the generally reduced identifiability of *both* targets in double target conditions (orange curves) compared to that predicted for two independent single targets (gray curves) with NEAR and MIDDLE target distances. Only with FAR distances did the two curves approach more closely.

All these observations are confirmed when the individual accuracy ratings of each observer are analyzed in detail. The scatter plots in Figures 10 and 14 reveal the overall biases between targets 1 and 2, which was only reduced when either *both* targets could not be identified (ratings near chance level) or were both correctly identified (ratings near 1) at long presentation times. On average, however, the accuracy ratings with target 2 were smaller than those with target 1; mean differences (target 1 – target 2) were 0.053 ±0.009 for Vernier's (Fig.10) and 0.053 ±0.007 for T's (Fig.14).

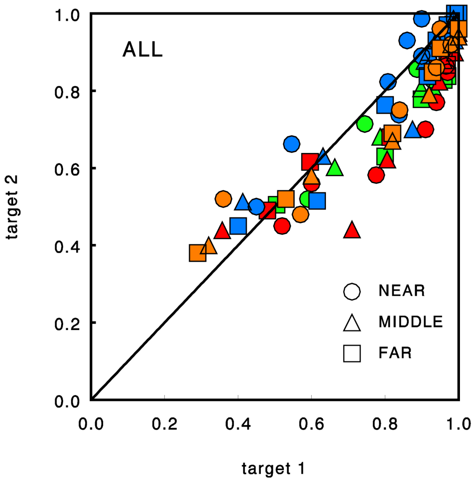


Figure 10. *Scatter plot of target 1 vs. target 2 ratings in Experiment 2.* Presentation as in Fig.6. As seen in the mean data of Fig.9, the identification of target 1 was generally better than that of target 2.

The individual data also show a strong deviation between predicted and measured identification rates of target pairs (Fig. 11a, 15a), with mean deviations (predicted – measured) of 0.080 ±0.012 *(Vernier's)* and 0.078 ±0.009 *(T's)*. Similar to Figure 7, these deviations were sorted for target distances and locations in different visual hemifields; the according cumulative distributions are plotted in Figure 11b-d, for Vernier's, and Figure 15b-d, for T's. In both experiments, deviations with NEAR distances were notably larger than deviations with FAR distances (red vs. blue curves in Figs.11b and 15b), while deviations with MIDDLE distances (green curves) were either similar to NEAR (Fig.11b) or FAR distances (Fig.15b).

Analysis of target locations in visual hemifields. When a distinction was made between target pairs that happened to fall into one or two visual hemifields (which was only possible for targets in the MIDDLE distance condition), the differences in mean deviations were not pronounced (Figs. 11c and 15c). Together with the collection of NEAR (all in same hemifields) and FAR

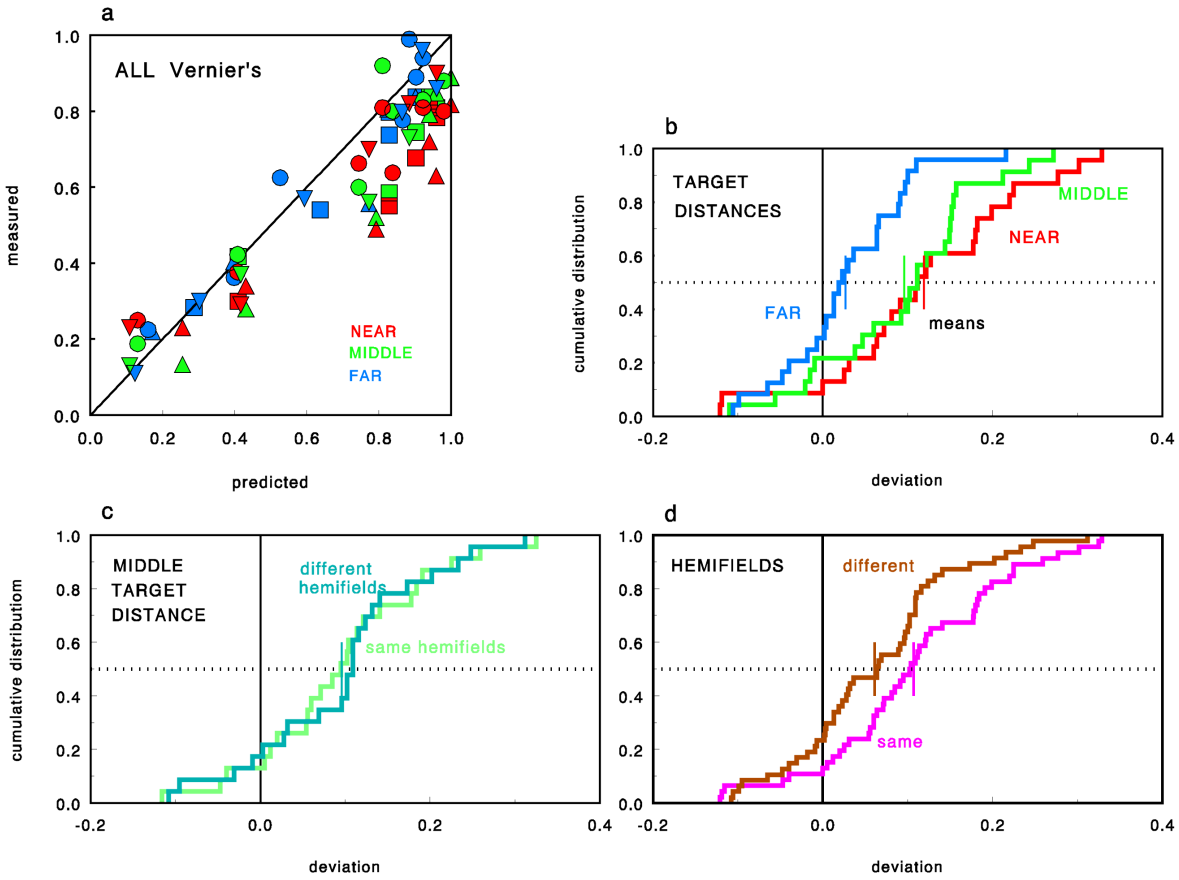


Figure 11. *Performance with target pairs in Experiment 2.* **a.** Deviations of measured from predicted target identifications; **b.-d.** accumulated deviation distributions for different conditions in *(a)*. Presentation as in Fig.7.

target distances (all in different hemifields), however, analysis still revealed a strong difference between *same* and *different* hemifields conditions (Fig.11d and 15d).

The findings are summarized in Figure 12. With pure distance analysis (red, green, blue data points, black curve), there is a strong decay of deviations from NEAR to FAR distances both for Vernier's (Fig.12a) and for T's (Fig.12b). Target interactions were strongest with NEAR (red), and smallest with FAR distances (blue); deviations with MIDDLE target distances were either similar to those in NEAR or those in FAR distance conditions. The hemifield analysis did not notably modify these values; in the overall analysis of target combinations in *same* or *different* visual hemifields (dashed curves in Fig.12), either the NEAR or the FAR distance deviations dominated. Altogether thus, the identification of double targets was modulated by two parameters, distance and hemifield locations, that could however not be distinguished in the present data.

Statistics. The observation that performance accuracy increased with increasing presentation time is obvious from Figures 9 and 13 and statistically significant in the present data. The Mann-Whitney U-test revealed significant differences in accuracy between the 3-4 shortest and the 2-3 longest presentation times tested of each observer, both for Vernier's (NEAR, $n_1=13$, $n_2=10$, $U=4$, $U_{krit}=14$, $p<0.001$; FAR, $n_1=13$, $n_2=11$, $U=4.5$, $U_{krit}=17$, $p<0.001$) and T's (NEAR, $n_1=17$, $n_2=16$, $U=9$, $U_{krit}=47$, $p<0.001$; FAR, $n_1=n_2=16$, $U=9.5$, $U_{krit}=43$, $p<0.001$).

Different to Experiment 1, identification rates for targets 1 and 2 in target pairs were not the same but differed significantly ($p<0.0001$; Wilcoxon signed-rank

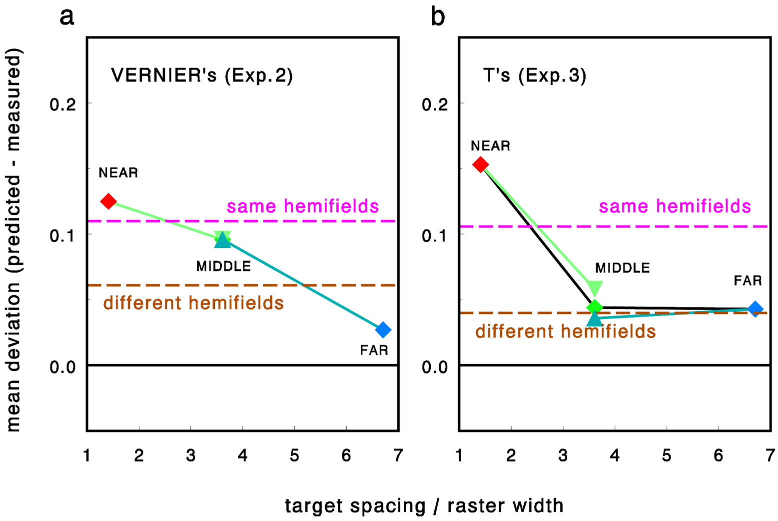


Figure 12. *Distance and hemifield effects in Experiments 2 and 3.* Presentation as in Fig.8. **a., b.** Mean deviations as plotted in Fig.11b-d (Vernier's) and Fig.15b-d (T's). All NEAR target pairs were located in *same*, all FAR target pairs in *different* visual hemifields.

test; *Vernier's;* N=78, $|z|$=5.05; *T's;* N=107, $|z|$=6.17). The similar ratings with single targets and target 1 in FAR target pairs (Figs.9 and 13, black vs. red curves) was also seen in the full analysis of data pairs from all observers. While target 1 ratings always differed significantly from single target ratings, they did not with FAR target pairs (Wilcoxon signed-rank test; single vs. target 1; *Vernier's,* N=22, W=118.5, W_{krit}=65, *n.s.*; *T's,* N=31, W=207, W_{krit}=147, *n.s.*).

Deviations between predicted and measured accuracy data for target pairs were significant in almost all subgroups (*Vernier's:* $N \geq 22$, $W \leq 24$, $W_{krit} \geq 30$, $p<0.001$ for NEAR and MIDDLE distances; $N \geq 45$, $|z| \geq 3.84$, $p<0.0001$ for target locations in same and different hemifields; *T's:* $N \geq 34$, $|z|$=5.11, $p<0.0001$ for NEAR, $|z| \geq 3.34$, $p<0.001$ for MIDDLE and FAR, $|z| \geq 2.91$, $p<0.005$ for MIDDLE distances in same or different hemifields; and $N \geq 69$, $|z| \leq 4.48$, $p<0.0001$ for the overall

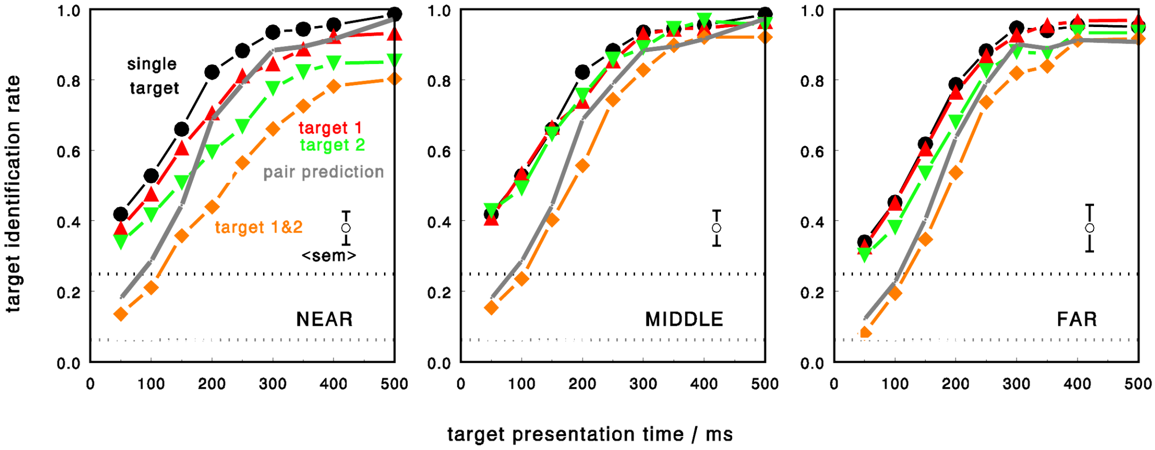


Figure 13. *Mean performance in Experiment 3 (T's).* Presentation as in Fig.5. T's were difficult to identify and required long presentation times (like the Vernier's in Fig.9). The identification of target 1 (red) was often better than that of target 2 (green). Performance with target pairs was generally reduced below predictions, but least reduced in FAR target conditions. And only in FAR distance conditions did the identification of target 1 in target pairs reach that of single lines. Note that the chance level in the identification of single targets was 0.25 (black dotted lines) and that of target pairs 0.0625 (gray dotted lines).

samples of targets in same and different hemifields). The only exception was the subgroup of *Vernier's* at FAR distance, for which the deviations were not significant (N=24, W=89; W_{krit}=81).

The overall differences between deviations in distance conditions (NEAR; MIDDLE; FAR; Figs.11b and 15b) were significant (ANOVA; *Vernier's*, $F(2,67) = 5.01$, $p<0.005$; *T's*, $F(2,106) = 25.42$, $p<0.0001$) and also between the data samples of same and different hemifields conditions (Figs.11d and 15d; *Vernier's*, $F(1,91) = 4.91$, $p<0.05$; *T's*, $F(1,142) = 20.82$, $p<0.0001$), but not in the small subdivision of MIDDLE distance conditions with targets in same vs. different hemifields (Figs.11c and 15c; *Vernier's*, $F(1,44) = 0$; and *T's*, $F(1,68) = 1.23$).

Discussion. In principle, the performance variations with Vernier's and T's (Exp.2 and 3) were similar and both not much different from the performance variations seen with oblique oriented lines (Exp.1). The identification of target pairs was always poorer than that of single targets, but while in FAR conditions the deterioration was mostly predicted by the reduced identification rate of double compared to single targets, target identification was further disturbed for targets in NEAR and MIDDLE distance conditions. Together with the findings of Experiment 1 it is obvious that this stronger distortion is not an effect of unclear selection – both targets were easily detected – but had to do with the *identification* of cued targets which was obviously disturbed when targets were located closely together. A notable difference to Experiment 1, however, is the bias between target 1 and target 2 which had been identified about equally well for oblique lines but were identified at different accuracies with Vernier's and T's. This is likely due to the more difficult discrimination of these targets and the need of longer presentation times than for the oblique lines (cf. black curves in Figs. 5, 9 and 13), which might have generated a systematic bias in target analysis in favor of the target the properties of which had to be entered first. This bias was present in all tests of Experiments 2 and 3 (except for T's in MIDDLE distance) and only disappeared when target presentation time was long enough so that both targets could be correctly identified.

Note that performance characteristics in Experiments 2 (Vernier's) and 3 (T's) were quite similar, although different responses had to be made with these targets. With Vernier's, observers had to discriminate between *two* displacements (resulting in seemingly left- or right-tilted lines); with T's, observers had to discriminate between *four* different orientations of the T. This is reflected in the different chance levels, 0.5 with Vernier's and 0.25 with T's (black dotted lines). For target *pairs*, these rates must be multiplied and result in chance levels of 0.25 and 0.0625, respectively, for target combinations (gray dotted lines). Thus, the identification of individual targets in pair configurations (e.g., the red curves in NEAR conditions) should strongly deviate from the gray curves. For single Vernier targets, for example, even for those in pair configurations, the chance level is 0.5 but for Vernier target pairs only 0.25. Thus, the partial coincidence of red and gray curves with NEAR targets in Figures 9 and 13 (and also Fig.5) is merely accidental.

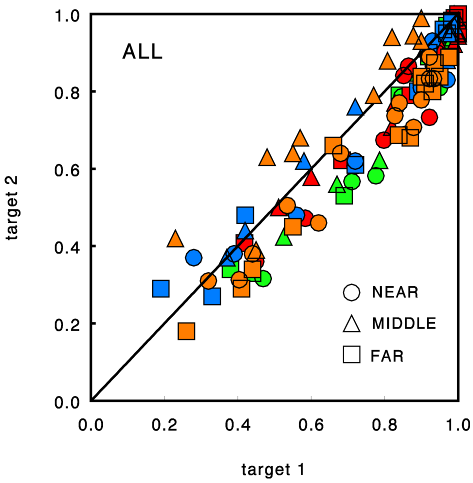


Figure 14. *Scatter plot of target 1 vs. target 2 ratings in Experiment 3.* Presentation as in Fig.6. The identification of target 1 was generally better than that of target 2.

Experiment 4: Colored lines

In the final experiments, a *conjunction* target was used composed of features from different dimensions, here color and orientation. Such targets had been assumed to require focal attention to be correctly identified (Treisman & Gelade, 1980).

Targets were oblique lines, like in Experiment 1, now colored red or green (Fig.1). Observers had to identify cued targets as one of four possible templates (red or green lines tilted to the left or right) and, in the case of target

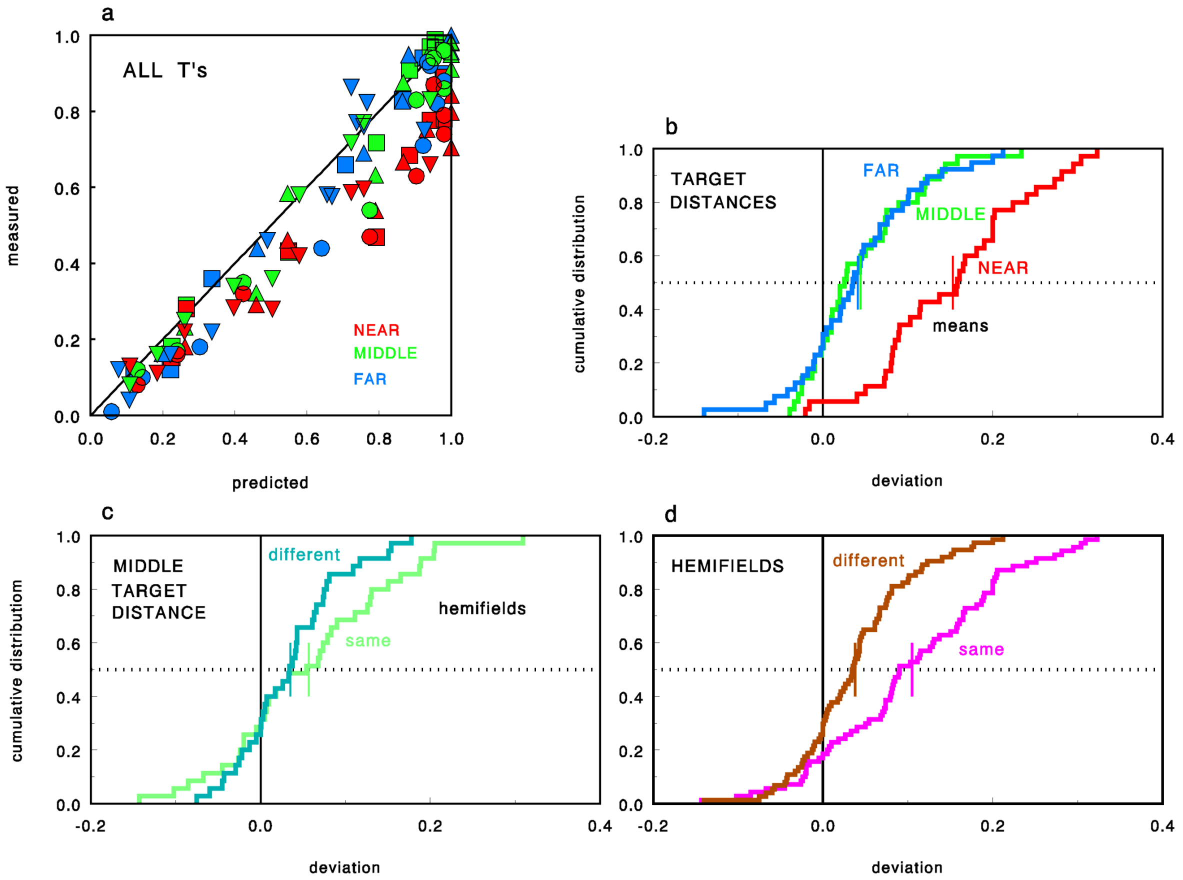


Figure 15. *Performance with target pairs in Experiment 3.* **a.** Deviations of measured from predicted performances; **b.-d.** accumulated deviation distributions for different conditions in *(a)*. Presentation as in Fig.7.

pairs, make that identification for both targets in sequence, from left to right, as in the previous experiments.

Performance characteristics. The mean accuracy variations with presentation time are shown in Figure 16. Although target responses were more complicated than in Experiment 1, the general timing and accuracy variations were similar. With single targets, the means reached ratings of 0.9 or more (almost 0.9 at FAR distances) with target durations of 100 ms, and there was a similar ranking between observers (not shown). One observer reached that level with presentation times of only 40 ms; others needed longer stimulus presentations (up to 120 ms). Other aspects were also similar to Experiment 1; attentional and perceptual resources were equally distributed between the two targets (red and green curves), except in FAR distance conditions, and double target ratings (orange) were far below the expected ratings for two independent single targets (gray and black curves), particularly in NEAR and MIDDLE distances. This indicates that targets were not identified as two independent single lines but showed a strong interference between each other. For target pairs in FAR distance, however, the response pattern changed. Ratings of (the left-hand) target 1 were now as accurate as those of single targets, while the ratings of target 2 were slightly deteriorated. The deviations between predicted (gray) and measured target pair identifications (orange) were smaller than at other distances but still present. Again, there were notable variations between observers. One observer had identified target pairs at FAR distance almost exactly as predicted (orange vs. gray curves superimposed), and the rating differences between

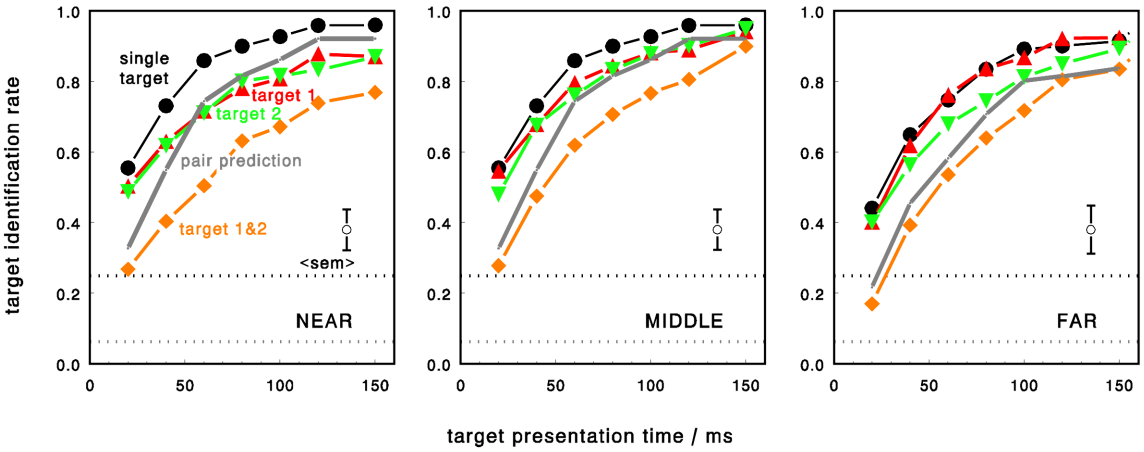


Figure 16. *Mean performance in Experiment 4 (conjunctions).* Presentation as in Fig.5. Conjunctions of color & orientation were faster identified than Vernier's and T's and reached high identification rates at similar presentation times as (non-colored) oriented lines (Exp.1). The identification of targets 1 and 2 (red and green) was equally good, except at FAR distances. Performance with target pairs was generally reduced below predictions but least in FAR target conditions. And only in FAR distance conditions did the identification of target 1 in target pairs reach that of single lines. Chance levels in single target and target pair identifications were 0.25 (black dotted lines) and 0.0625 (gray), respectively.

targets 1 and 2 in the means (red vs. green curves) were not seen in all observers. It is therefore important to look at rating differences in the individual observers' data.

Little bias between targets. Figure 17 shows the scatter analysis of target 1 and target 2 identifications in all tests of Experiment 4. Different to Figure 6 for white oriented lines, there is now indeed a small bias (mean differences *target 1 – target 2*: 0.026 ±0.008 for all tests) which is however dominated from the FAR distance conditions (NEAR, 0.006 ±0.010; MIDDLE, 0.015 ±0.015; FAR, 0.053 ±0.014). The analysis thus confirms the impressions we have got from the mean performances in Figure 16. With NEAR and MIDDLE target distances, targets 1 and 2 were identified with similar accuracy; with FAR distances, the left-hand target was slightly preferred and reached the same accuracy as single targets, in the means.

Distance and hemifield analysis. The deviations between predicted and measured double target identifications are summarized in Figure 18. The overall deviations from predictions were quite strong (Fig.18a; mean deviation 0.103 ±0.010), but the strengths varied between target distances (Fig.18b) and between conditions in which the two targets were located in same or different visual hemifields (Fig.18c and d). This is clearly visible in the mean deviation data shown in Figure 19a. Deviations diminish with increasing target distance (black line); however, this variation was associated with the placement of targets in either same or different visual hemifields (dashed lines). Only for targets in MIDDLE distance could these latter conditions be distinguished.

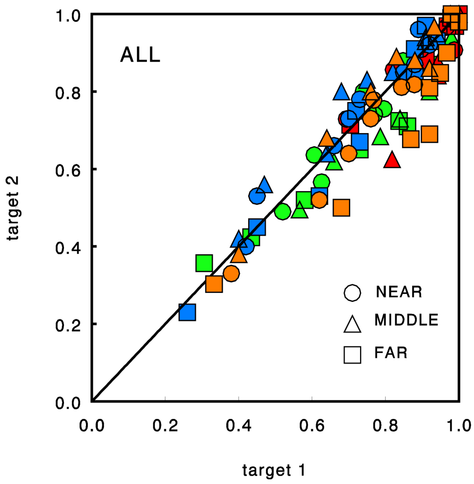


Figure 17. *Scatter plot of target 1 vs. target 2 identifications in Experiment 4.* Presentation as in Fig.6. Target 1 and target 2 identifications differed merely in FAR target conditions (squares).

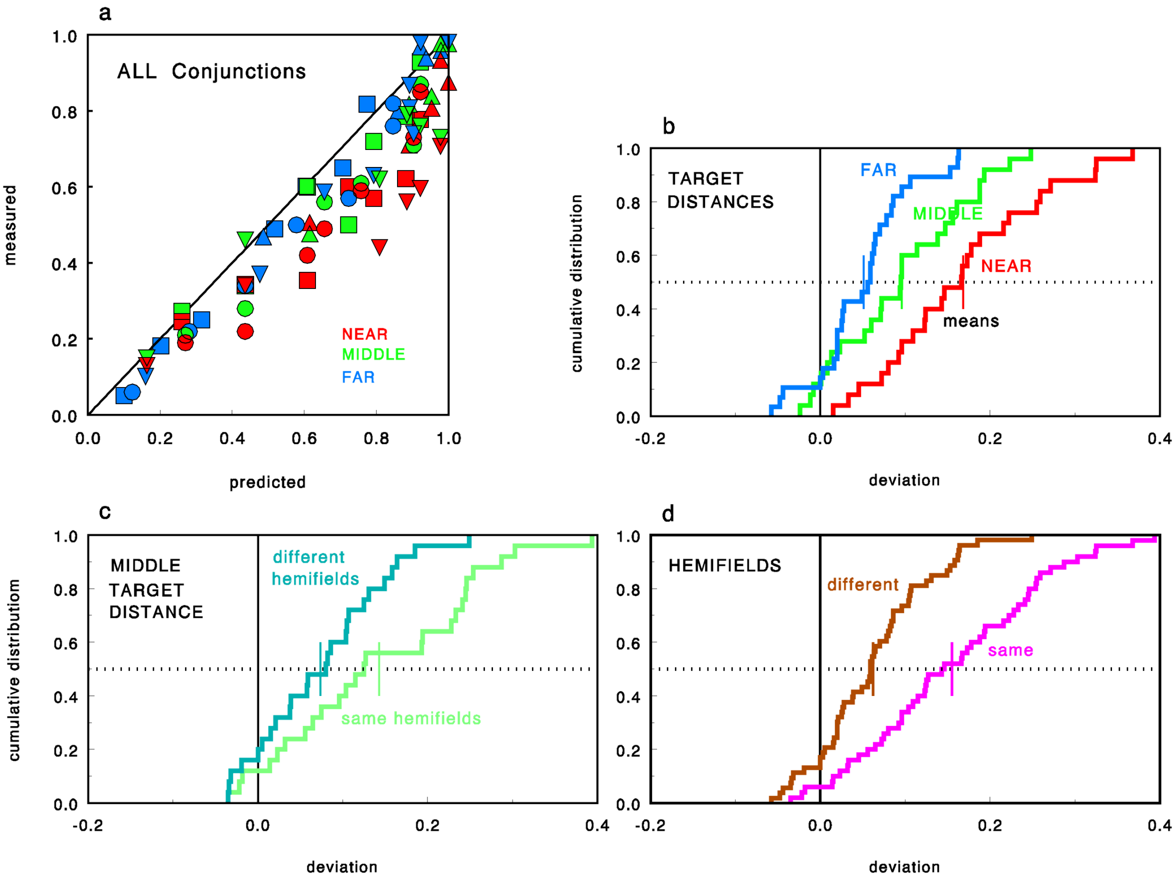


Figure 18. *Performance with target pairs in Experiment 4.* **a.** Deviations of measured from predicted identification data; **b.-d.** accumulated deviations for different conditions in *(a)*. Presentation as in Fig.7.

Statistics. The increase of performance accuracy with presentation time was statistically significant (Mann-Whitney U-test of accuracy differences between the shortest and longest presentation times tested for each observer; NEAR, n_1=12, n_2=11, U=14, U_{krit}=15, p<0.001; FAR, n_1=13, n_2=12, U=20, U_{krit}=20, p<0.001).

The difference between 1st and 2nd target identifications in target pairs was not significant for NEAR and MIDDLE target distances (Wilcoxon signed-rank test; N=25, $|z| \leq 0.98$) but was significant for FAR target distances (N=28, $|z|$=3.2, p<0.001); target 1 was then better seen than target 2. In turn, the differences between single targets and individual targets in target pairs were always significant, except for the target 1 in FAR distances (Fig.16, black and red curves; Wilcoxon signed-rank test; N=26, W=139.5, W_{krit} = 98, *n.s.*).

The deviations between predicted and measured accuracy data in target pairs were highly significant in all subsamples of the data in Figure 18b-d (NEAR, MIDDLE, FAR distances; MIDDLE same and different hemifields; and full samples of same and different hemifields; Wilcoxon signed-rank test, $n \geq 24$, $|z| \geq 3.69$, p<0.005).

Also the *differences* between deviations in the various subgroups were significant (ANOVA; NEAR, MIDDLE, FAR, Fig.18b, $F(2,75) = 15.27$, p<0.0001; MIDDLE, same and different hemifields, Fig.18c, $F(1,48) = 6.27$, p<0.02; overall data in same and different hemifields, Fig.18d, $F(1,101) = 29.52$, p<0.0001). When individual conditions were compared using the Mann-Whitney U-test, however, there was a ranking in significance levels from MIDDLE same vs. different and FAR vs. MIDDLE (both p<0.05) over NEAR vs. MIDDLE (p<0.01) to

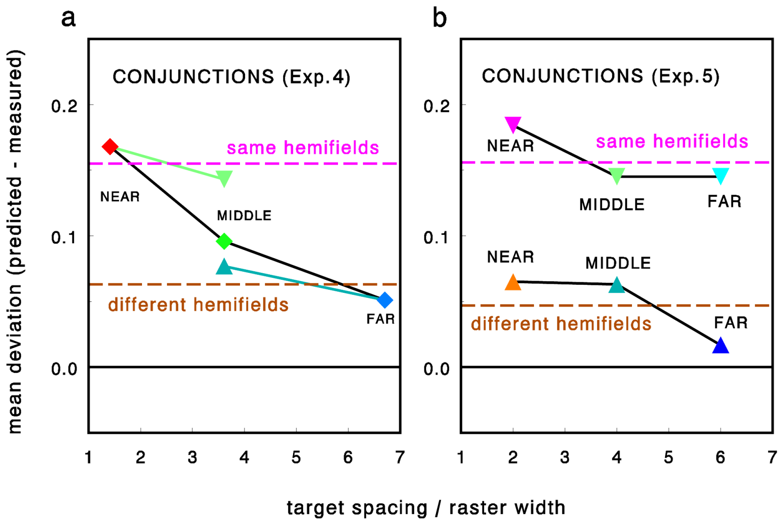


Figure 19. *Distance and hemifield effects in Experiments 4 and 5.* Presentation as in Fig.8. Colored symbols and dashed lines show mean deviations as plotted in Fig.18b-d and Fig.23b-f. **a.** In Experiment 4, all NEAR target pairs were located in *same*, all FAR target pairs in *different* visual hemifields. **b.** When distance and hemifields were distinguished and missing conditions added (Exp.5), data reveal a strong predominance of hemifield effects.

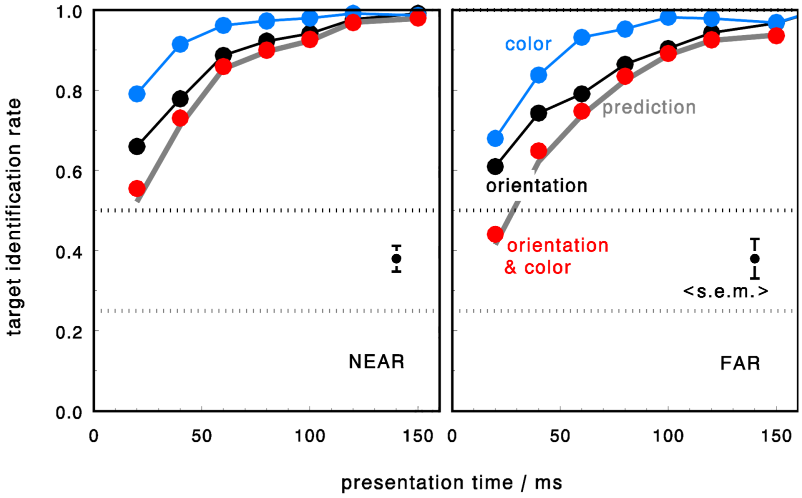
NEAR vs. FAR and *same* vs. *different* hemifields (both $p<0.0001$), as is suggested by the relative spacing of the according cumulative distributions in Fig.18b-d.

Incidental finding: No synchronous binding of orientation and color. It has been a long-standing model that different features of an item must be attentively bound for the correct perception of that object (Treisman & Gelade, 1980; Treisman, 1985). If presentation time is too short so that the attentional resources cannot yet be focused upon the object, the binding may fail and false conjunctions of different features might be perceived instead (Treisman & Schmidt, 1982). In a recent study with cued conjunction targets as in Experiment 4, I could show that color and orientation are processed independently of each other and, what would be most important in this context, are identified at different speed (Nothdurft, 2020; see also Moutoussis & Zeki 1997). Color is generally faster identified than orientation. Thus, even when attention is cued to the target location, observers may indicate false conjunctions just because one feature could not yet be reliably identified. These findings, already reported and carefully discussed elsewhere (Nothdurft, 2020), were here confirmed on three new observers. Figure 20 illustrates the difference in the identification of single targets. While the identification rates of conjunction targets (red symbols) increased with presentation time, the accuracy in color identification (blue curves) was always better than the accuracy in orientation identification (black curves). The differences were highly significant (Wilcoxon signed-rank test on the individual data from all observers; $N=47$, $|z|=5.12$, $p<0.0001$).

Discussion. Surprisingly or not, the performance variations with conjunctions targets (orientation & color) in Experiment 4 were not much different from the performance variations with white oriented lines in Experiment 1. The identification of target pairs was always poorer than predicted from single targets; the deviation was strongest for targets in NEAR and MIDDLE distances. At these distances in particular, the two targets in target pairs were seen equally good, and sometimes as good as predicted for independent targets. Thus, there is no indication that targets had not been selected in parallel. What differed however, was the simultaneous target *identification*, i.e. the likely attentive process, which was most strongly deteriorated when the two targets were located close together. It is not clear why target 1 was slightly better seen than target 2 in FAR target pairs. The difference was strongest in two observers who required particularly long target presentations (but still below 150 ms) to reach high accuracy. These difficulties might have biased them to concentrate on the left-hand target first, at FAR target distances and accordingly large eccentricities.

We have seen in Experiments 1-4 that target distance had a strong effect on the accuracy at which double targets could be identified. We have also seen that another

Figure 20. *Incident observation: color is faster identified than orientation*. Mean identification rates with single targets in NEAR and FAR distance conditions. The figure confirms an earlier finding on the cued visual selection of conjunction targets (Nothdurft, 2020), here with three new of the four observers. When looking at the correct color (blue) and orientation responses (black) to a series of conjunction targets (red), the color was always better seen than the orientation. Predictions (gray) were made for the extracted color and orientation responses and must fit the original conjunction measures from which the component data were extracted.



important parameter may be whether the two targets were presented in one or two hemifields. Unfortunately, in the patterns used so far, these two parameters were correlated; NEAR target pairs were always presented in the *same* hemifield, and FAR target pairs always in *different* hemifields. In the following experiment, the test series of Experiment 4 was repeated with new target locations which now allowed to disentangle distance and hemifields variations and look at both parameters independent of each other.

Experiment 5: Colored lines at new locations

The same test patterns as in Experiment 4 were used but targets were now placed within or between hemifields at the same distances in both conditions (Fig.3). Since target eccentricity varied between NEAR, MIDDLE, and FAR distances, there were also three conditions for single targets which occurred at similar locations and same eccentricities. As in the previous experiments, target identifications had to be entered in sequence beginning with the left-most target. Different to the previous experiments, however, targets could now also appear in the same raster column; in that case the upper target had to be entered first. All subjects quickly learned the new rule. Experiment 5 was run on three observers at the end of the project after one observer had already left.

Better identification of targets in different hemifields. Figure 21 shows the mean accuracy ratings in selected target conditions. Performance differed strongly between NEAR, MIDDLE, and FAR target conditions; even single targets (black curves) were less quickly, and less accurately, identified at FAR target locations than at target locations used with the NEAR or MIDDLE distance conditions. The different ratings led to different predictions for the identification of (independent) double targets in these three conditions (gray curves); of course, no distinction was made in predictions between targets in same and targets in different visual hemifields. In experiment, however, these conditions produced quite different accuracy data. Target pairs in *same* hemifields generated fewer correct responses, at any presentation time, than target pairs in *different* hemifields. With FAR distances, the data from different hemifields fell closely upon the predictions from single targets, suggesting that FAR targets in different hemifields were indeed processed independently of each other. Performance in the same hemifields conditions were, however, still notably disturbed. At smaller target distances, NEAR and MIDDLE, not only the same hemifields data but also the different hemifields data were deteriorated compared to the predictions.

Performance bias between targets. The target interactions are further analyzed in Figures 22 and 23. According to the scatter plot of individual performance data in Figure 22, the ratings for target 1 and target 2 again differed; in this experiment, however, target 2 was slightly better seen than target 1. Mean differences (*target 1 – target 2*; -0.048 ±0.011) are displaced upwards from

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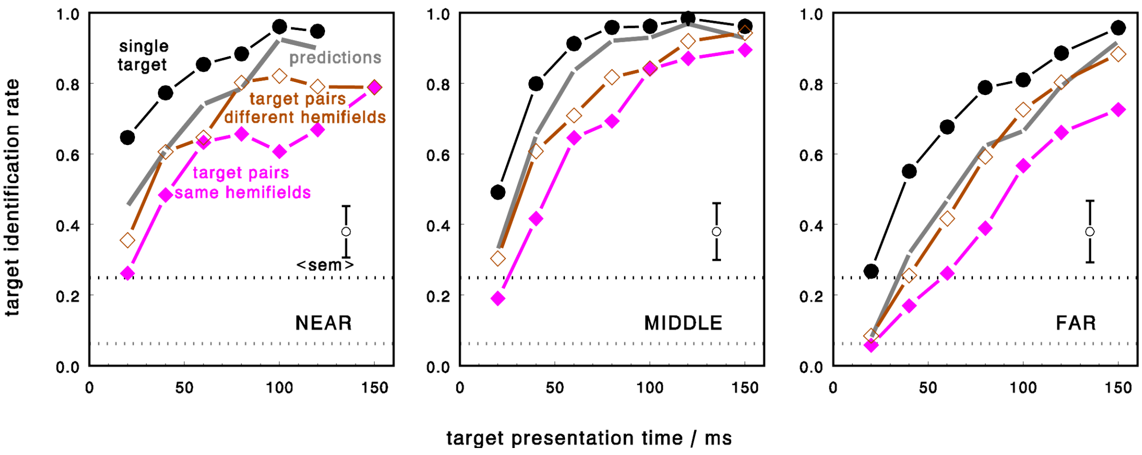

Figure 21. *Mean performance in Experiment 5 (conjunctions; new target configurations).* In this experiment, targets were presented, at various distances, in same and different hemifields (see Fig.3). Single targets occurred at same eccentricities. Of various combinations, here only four curves are shown; the performance ratings with single targets (black), the predictions for two independent targets (gray), and the measured performance rates with target pairs in same (magenta) and different hemifields (brown, open symbols). Otherwise, presentation as in Fig.16. With all target distances, the performance with targets located in same hemifields was poorer than the performance with target pairs in different hemifields, and only at FAR distances did the latter reach the predictions made for independent single targets.

identity (oblique midline). An interpretation of this bias is less obvious than in Experiments 2-4, however. Target responses had still to be entered in sequence beginning with the left-most (or upper) target (target 1) then followed by the other target located more to the right or below. Instead of concentrating primarily on the left-hand or upper target, as seen in the previous experiments with difficult targets, observers now made, on average, more accurate responses to the right-hand or lower targets.

Distance versus hemifield analysis. The comparison of predicted and measured performances, however, revealed large deviations (Fig.23a; mean deviation between predicted and measured performances 0.101 ±0.012) that differed systematically between the various distance and hemifield conditions (Fig.23b-f). Cumulative distributions reveal large differences between target pairs in same and different hemifields, at all target distances (Fig.23b-d). When data are accumulated in subgroups of same and different hemifields conditions, the difference remains large (Fig.23e). However, when the data from same and different hemifields are accumulated within the individual distance groups, the remaining overall distance effects become rather small (Fig.23f). This is summarized in Figure 19b.

Experiment 5a. Non-colored lines (cf. Exp.1). The new set of target locations used in Experiment 5 was also tested by one observer in Experiment 5a, with partly similar results (Fig.8b). Deviations between predicted and measured performance data were small when targets were placed in *different* hemifields, and large when targets were

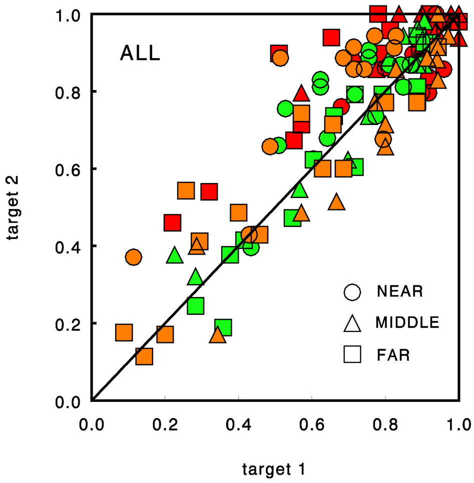

Figure 22. *Scatter plot of target 1 vs. target 2 identifications in Experiment 5.* Data reveal a significant bias for target 2.

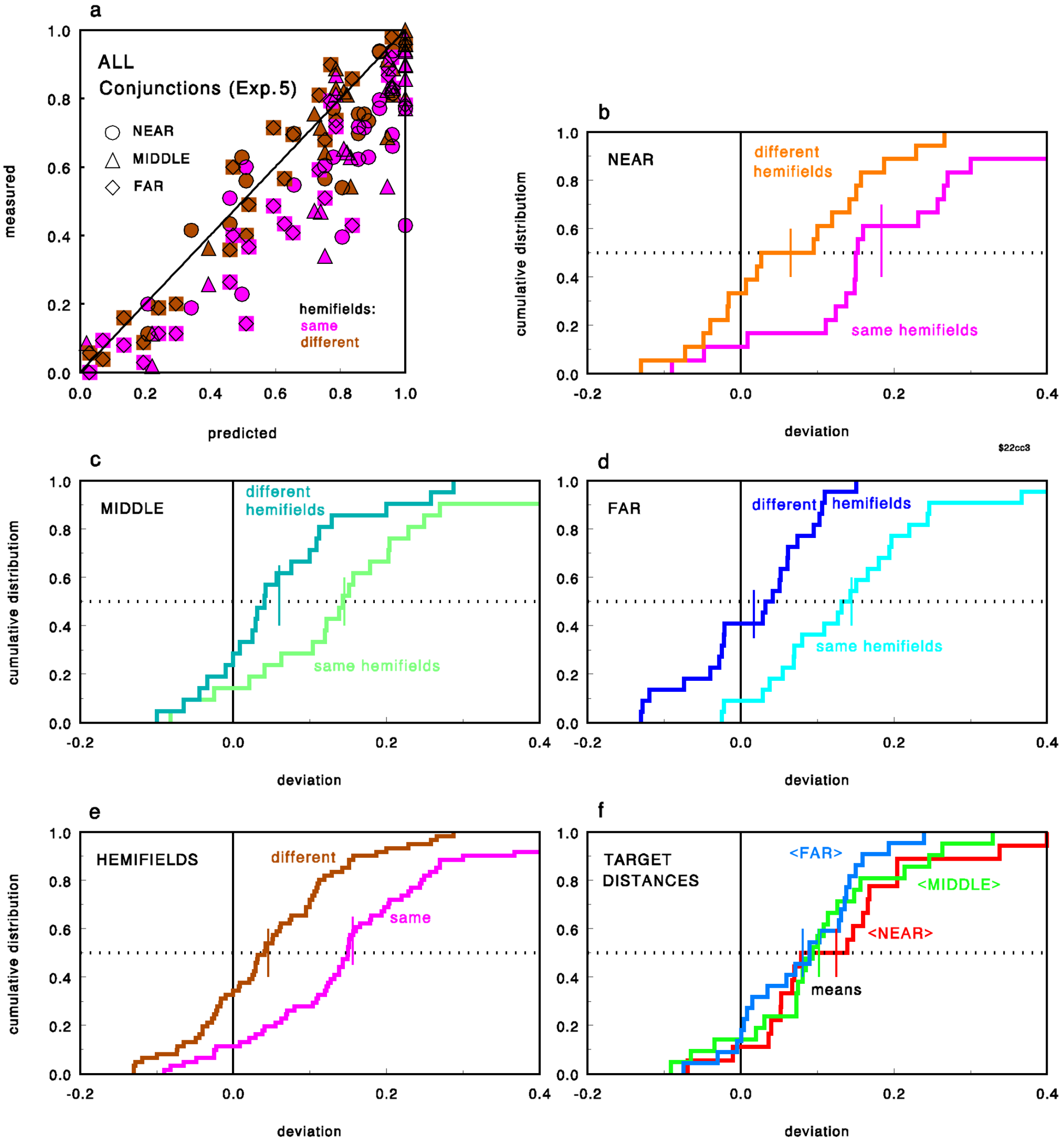

Figure 23. *Performance with target pairs in Experiment 5.* **a.** Deviations of measured from predicted identification data; **b.-f.** accumulated distribution of deviations in different conditions of *(a)*. Similar presentation as in Fig.7. The new conditions in this Experiment 5 allow for direct hemifield comparisons at each tested distance *(b-d)*. Target pairs in same hemifields always produced larger deviations than target pairs in different hemifields. This difference maintains when conditions are pooled for same and different hemifield conditions *(e)* but not when pooled for similar distances *(f)*.

located in *same* hemifields (Fig.24a). Within groups, however, there was almost no distance modulation (Fig.24b), neither in *same* nor in *different* hemifields (Fig.8b).

Statistics. The identification of single targets was significantly better, for same durations, at target locations in NEAR or MIDDLE than in FAR conditions (Fig.21; Wilcoxon signed-rank tests, $N \geq 18$, $W \leq 8.5$, p<0.001); the differences between NEAR and MIDDLE target locations themselves were not significant (N=16, $W = 55$).

Overall, the performance bias between targets 1 and 2 (Fig.22) was significant in the full data sample (Wilcoxon signed-rank test; N=111, $|z|$=3.77, p<0.0001)

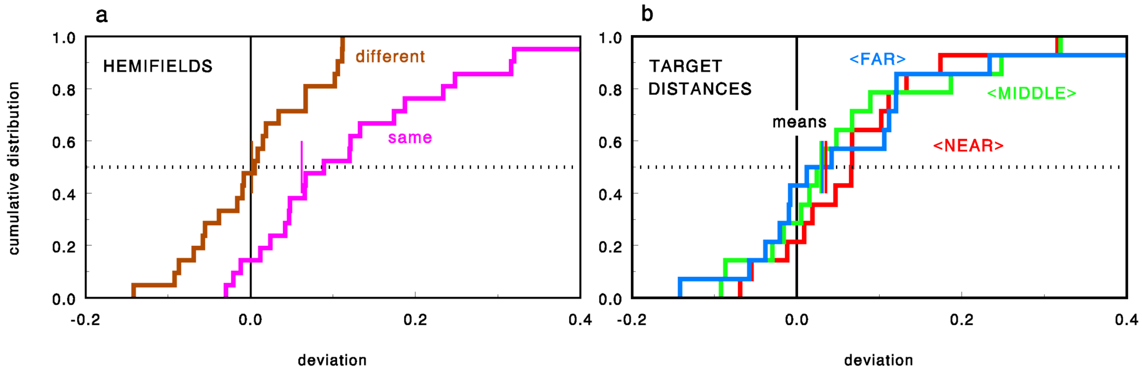

Figure 24. *Performance with target pairs in Experiment 5a (orthogonal lines).* Accumulated deviations for **a.** same vs. different hemifield conditions irrespective of target distance, and **b.** different target distances irrespective of hemifield locations (Fig.23e, f). The deviations of measured from predicted data are small for targets in different hemifields and large for targets in same hemifields *(a)*; variations with target distance disappear *(b)*.

but significance levels varied between conditions. For FAR distances and in the accumulation of same hemifields conditions, the bias was less pronounced ($N \geq 39$, $2.14 \leq |z| \leq 2.16$, $p<0.05$) than for NEAR distances and all different hemifields conditions ($n \geq 36$, $|z| \geq 3.12$, $p<0.001$). For MIDDLE target distances, there was no significant bias at all (N=36, $|z|$=1.01). Also interesting is the accuracy of individual target ratings in target pairs in comparison to the accuracy of single targets. Only in a few conditions, all with targets in *different* hemifields, were these differences non-significant; with FAR distances between single targets and both target 1 and target 2, with MIDDLE and NEAR distances between single targets and target 2 only (Wilcoxon signed-rank test; $N \geq 17$, $W \geq 51$).

Deviations between predicted and measured accuracy data with target pairs (Fig.23) were significant in all *same* hemifields subgroups (Wilcoxon signed-rank tests; NEAR, MIDDLE, FAR distances, Fig.23b-d, $n \geq 18$, $W \leq 13$, $W_{krit} \geq 14$, $p<0.001$; and in the accumulated same hemifields group, Fig.23e; N=66, $|z|$=6.32, $p<0.0001$). In the according *different* hemifields data samples, deviations were only significant for NEAR (Fig.23b; N=18, W=38, W_{krit}=40, $p<0.05$) and MIDDLE (Fig.23c; N=20, W=42, W_{krit}=45, $p<0.025$) but not FAR distances (Fig.23d; N=22, W=90, W_{krit}=65) and also significant in the accumulated data sample across hemifields (Fig.23e; N=60, $|z|$=3.25, $p<0.001$). Deviations remained significant when data from target pairs in same and different hemifields at a given distance were accumulated (Fig.23f; $n \geq 36$, $|z| \geq 4.13$, p<0.0001).

The differences *between* curves in Figures 23b-d, i.e. between target pairs in same vs. different hemifields, were all significant, at different significance levels, both for subgroups at the selected target distance (ANOVA; NEAR, $F(1,34) = 6.93$, $p<0.02$; MIDDLE, $F(1,40) = 5.62$, $p<0.05$; and FAR, $F(1,42) = 18.93$, $p<0.0001$) and for the accumulated data samples of same vs. different hemifields conditions (Fig.23e; $F(1,120) = 27.68$, $p<0.0001$). The differences between accumulated distance data (Fig.23f) were not significant, however; F(2,58) = 0.95.

Experiment 5a. The data sample from Experiment 5a is small (one observer) and not sufficient to evaluate all conditions statistically. The overall performance variations between targets 1 and 2 were not significant (Wilcoxon signed-rank test; N=39, $|z|$=0.75). Deviations between predicted and measured accuracy data were generally just significant for target pairs in *same hemifields* (Wilcoxon signed-rank test; N=7, $W \leq 2$, W_{krit} =2, $p<0.05$) but not for target pairs in *different hemifields* (N=7, $W \geq 8$). This was also true for the accumulated data (Fig.24a; N=21, W=10, W_{krit} =25, $p<0.001$; and W=108, *n.s.*; respectively). The differences between curves obtained for target locations in same or different hemifields were significant (Fig.24a; ANOVA; $F(1,40) = 14.85$, $p<0.0005$) but not the differences between distance curves (Fig.24b; $F(2,39) = 0.03$).

Discussion. The differences between Figure 19a and b, and between Figure 8a and b are quite obvious. When the distance conditions NEAR and FAR that had contained exclusively same or different hemifields conditions in the previous experiments (Fig.19a), were now tested with the missing hemifield conditions, performance changed dramatically (Fig.19b). At NEAR distance, *different* hemifields conditions now generated small deviations between predicted and measured data, and at FAR distance, *same* hemifield conditions now produced large deviations. This underlines the predominance of hemifield effects in target pair analysis.

Figure 21 underlines the influence of target eccentricity on the identification speed (see, e.g., Benso, Turatto, Mascetti, & Umiltá, 1998). *Single targets* (black curves) at far distance from the fixation point (FAR condition; target eccentricity 7.6 deg; see Fig.3) were less rapidly (and, at a given presentation time, less accurately) identified than single targets associated with smaller pair distances (MIDDLE and NEAR; target eccentricities 5.1 deg and 2.5 deg, respectively). Variations with target eccentricity in cued visual selection have been reported earlier and may be explained by crowding effects (Nothdurft, 2017a). They were also seen in Experiments 1-4; the eccentricity of single target locations in NEAR and MIDDLE conditions varied from 1.8 to 5.7 deg (Fig.3a) and that for target locations in FAR target conditions from 5.7 to 6.5 deg (Fig.3b). The resulting performance differences are obvious (black curves Figs. 5, 9, 13, and 16).

GENERAL DISCUSSION

In altogether five experiments, performance variations in the identification of target pairs were studied. If target identification is a capacity-limited process that cannot be performed in parallel on multiple targets, the identification of *two* targets should be reduced compared to that of a *single* target – a reduction that might be predicted as the combined probability to identify two independent single targets. In all experiments, however, double target identification was strongly deteriorated below these predictions when targets were located closely together and in the same visual hemifield. Only for targets in FAR distance (12 deg apart from each other and presented in different hemifields) was double target identification about similar to the predictions. Interestingly, these principle performance characteristics were similarly seen with all tested target types, although their identification had been associated with different attentional requirements in the literature. Thus, the identification of target orientation (Exp.1) and of conjunctions of color and orientation (Exp.4) showed similar performance variations; but conjunctions had been assumed to require high attentional resources for the binding of features (Treisman & Gelade, 1980) whereas the need of attention for simple orientation discriminations had been questioned (e.g., Braun & Julesz, 1998). As already pointed out, however, both assumptions may not be absolutely correct. Even orientation identification is clearly accompanied by shifts of attention to the target (Joseph & Optican, 1996; Nothdurft, 1999) and cannot be achieved "preattentively" (Joseph, Chun, & Nakayama, 1997; Theeuwes, Kramer, & Atchley, 1999; Inverso, Sun, Chubb, Wright, & Sperling, 2016); on the other hand, the special attentional demands of *feature binding* in color and orientation had not generally been confirmed (Braun & Julesz, 1998; Nothdurft, 2020), which does, however, not abolish the potential need of attention for target *identification*. Thus it is possible that Experiment 1 (pure orientation) and Experiment 4 (orientation and color) were both performed by similar (attentive) processes to which the fast and partly perhaps even preattentive processing of color might have been added (Braun & Julesz, 1998; Cheal & Lyon, 1992; see discussion in Nothdurft, 2020). The identification of Vernier and T targets was generally far more difficult, which became evident in two observations, the need for longer presentation times and a general bias for the target that had to be entered first.

The seemingly clear modulation of performance with target distances was questioned in Experiment 5 in which distance effects were separated from hemifield effects; both had been intermingled in Experiments 1-4. The new findings underline the predominance of hemifield effects, while distance variations were mostly averaged out. Target pairs presented in different visual hemifields were identified better and merely independent of each other, whereas targets presented in the same visual hemifield were less correctly identified and appeared to disturb each other. According to the findings in Experiment 5, distance variations between targets had only a little effect on this dichotomy. Unfortunately, the new design of test locations in Experiment 5 was developed at the end of the study, after analysis of the previous tests, and could only be tested on three observers who still were available; one observer run a similar additional test with the pure orientation targets from Experiment 1 (Exp.5a). Given the importance of the result, it would be helpful if additional tests on more subjects and with different targets would be performed.

The only distinction of distance and hemifield effects in Experiments 1-4 could be done for targets in the MIDDLE distance condition. It is not certain why this analysis generated so small performance variations compared to Experiments 5 and 5a (see Figs. 8 and 12). Only in Experiment 4 (with the same targets as in Experiment 5) differed the performance in the two hemifield conditions. The failure may however be due to a peculiarity of MIDDLE targets in Experiments 1-4. With target pairs in *same* hemifields, one of the two targets was necessarily located in the central raster column (see Methods and Figs. 2 and 3) and thus in a region which is represented in *both* hemispheres of the visual system. If targets pairs were located outside this region and clearly in either same or different hemifields, as in Experiments 5 and 5a (see Fig.2c), strong performance differences were also seen with MIDDLE target pair conditions.

Limiting factors in multiple target identifications. But why should two simultaneously cued targets, at all, be less accurately identified than one? What is the limiting factor in the perceptual process? In principle, two processes might have been affected; target selection and target identification (Sagi & Julesz, 1985; Nothdurft, 2002, 2006). *Target selection* might be disturbed when two (or more) targets are cued instead of one. There is a large number of studies in the literature that do not support this assumption, however. Salient targets are preattentively and, in parallel, detected and localized but not identified (Sagi & Julesz, 1985). In a related grouping experiment I could show that the configuration of multiple salient targets can be detected at once, but not their individual identities (Nothdurft, 1992). In a more recent study on serial search, the number of cued targets had a direct effect on the search time when search was to be performed within a subgroup of cued items; without cues however, search time was related to the total number of items in the pattern (Nothdurft, 2006). All these findings indicate that the selection of cued targets can be achieved in parallel. Also in the present experiments, observers could always tell whether one or two targets were cued, even though eventually only one of them was correctly identified.

This suggests that the limitations were associated with the second process, the *identification* of selected targets. At short durations, observers could eventually identify one or the other target; the correct identification of double targets was strongly deteriorated. But only when the two targets were presented in different hemifields (at FAR distances in Exp.1-4) did double target identification reach the predictions from single target data (gray curves in Fig.5 and 16).

There might have been a third limitation of target identification in the present experiments, the observer's *response*. In particular with double targets, sorting the perceived target identities into a correct sequence of key responses might have been a problem and might have limited performance. This aspect was not further analyzed in the present study. I was mainly interested in the differences between conditions (distance and hemifield variations) that were similarly affected by any response limitations. In earlier studies, however, I have sometimes noticed performance differences of up to 8-10% that were associated with the congruence of target locations on the screen and the location of according response keys on the computer keyboard (Nothdurft, unpublished data). A (pure) orientation target tilted to the left was more often identified correctly when located on the left-hand side of the screen than when located on the right-hand side, and *vice versa*. (This was also the case with one observer in the present study.) Such congruence effects were not seen with all observers and seemed to depend on their individual history in such tests. In a long-term study, for example, two observers showed target-response congruence effects after they had previously performed a target localization tasks in which they had to indicate the *side* of the screen where the target occurred. Two other observers who had not run such tests before did not show target-response congruence. In the present experiments, however, such effects cannot explain the performance differences between target distances or hemifield locations since all these variations were averaged out across trials. In addition, such congruence effects would not have been obvious and likely not present with other targets tested (e.g., T's, Exp.3).

The role of predictions in the analysis. The identification of target pairs in the present study was related to predictions made from single targets. By computing the *deviations* between predicted and measured accuracy data it came out that the identification of FAR target pairs or targets in different hemifields was less disturbed than that of NEAR target pairs or targets in same hemifields. This conclusion might have been erroneous, however. The inspection of Figure 5 and analogue figures from the other experiments shows that the responses to double targets (orange) varied far less between distance conditions than the responses to single targets (black). Since deviations were based on both curves, the observed variations between distance conditions might reflect not only a better performance with target pairs but also a worse performance with single targets in FAR compared to NEAR distance conditions. This is, in fact, quite obvious in Figure 5; the direct performance variations between NEAR and FAR *double* targets (orange) are smaller than the performance variations in the according single target conditions (black). The same is apparently true with the other targets (Figs. 9, 13, 16). Also, the identification of individual targets in pair conditions (red and green curves) varied less than the identification of single targets. The pattern was different in Experiments 5 and 5a (Fig.21). Here, performance ratings of targets in same hemifields were always lower than those of targets in different hemifields, despite the fact that single target ratings were also diminished with far target distances (i.e., larger eccentricity of targets) and thus predictions were lowered, too. Were the findings from Experiments 1-4 thus mainly artifacts from the variable performance with single targets?

I will discuss this issue from two sides. First, I will argue why single target performance was, and necessarily had to be, more strongly affected by the different distance conditions than double target performance. Second, I performed an additional analysis of double target identifications to see if these were indeed statistically distinct in the different distance conditions.

Performance variations with single targets. The observation that the identification of single targets varied with target eccentricity is not surprising (see also Benso, Turatto, Mascetti, & Umiltá, 1998) and likely the result of diminishing attentional resolution (Intriligator & Cavanagh, 2001) and increasing crowding effects (Nothdurft, 2017a) with increasing target eccentricity. But why was the identification of double targets not similarly affected? The explanation is likely the different locations of targets in single and double target patterns. While single targets in NEAR and MIDDLE conditions could occur close to the fovea, at small eccentricities, as well as farther away, at larger eccentricities, the probability that at least one of the two targets with MIDDLE or FAR distances occurred farther in eccentricity was strongly increased (see Fig.3). Thus, target pairs generally covered a wider range of eccentricities in Experiments 1-4 than single targets. Only in Experiments 5 and 5a, where single and double targets occurred at the same eccentricity, performance variations were also pronounced with double targets (Fig.21).

Direct comparison of double target performances. To verify the main conclusions from Experiments 1-4, I directly compared the performance variations with double targets at different distances in the full data set from all observers. Interestingly, performance variations were more pronounced between NEAR and MIDDLE target conditions (Wilcoxon signed-rank tests; *orientation*, N=39, $|z|$=4.9, p<0.0001; *Vernier's*, N=27, $|z|$=1.78, p<0.05; *T's*, N=38, $|z|$=5.2, p<0.0001; *conjunctions*, N=28, $|z|$=3.92, p<0.0001) than between NEAR and FAR target conditions (*orientation*, N=37, $|z|$=2.35, p<0.01; *Vernier's*, N=28, $|z|$=2.36, p<0.01; *T's*, N=40, $|z|$=3.45, p<0.001; *conjunctions*, N=28, $|z|$=1.14, *n.s.*). The performance with NEAR target distances was always worse than that with MIDDLE or FAR target distances, thus confirming the conclusions from Experiments 1-4. The differences were even stronger in Experiments 5 and 5a where also target pairs varied in eccentricity (Fig.3c). Double targets in different hemifields were always seen better than double targets in same hemifields (Fig.21). These differences were significant for each distance group (Exp.5; $n \geq 18$, $W \leq 21.5$, p<0.005) and for the cumulative data samples across all distances (Exp.5; N=60; $|z|$=5.68, p<0.0001; Exp.5a; N=20; W=11, W_{krit}=21, p<0.001). Overall, thus, response variations with double targets were real and not an artifact from the comparison with single targets.

Other algorithms. It might be reasonable to discuss the reliability of the exact algorithm used for predictions. When looking at probabilities, the probability of correctly identifying double targets should be given as the combined probability of identifying two independent single events, $p\ (t_1 + t_2) = p\ (t_1 \cap t_2) = p\ (t_1) \cdot p\ (t_2) = p^2\ (t)$, as described in the Methods section. This algorithm takes care of the reduced chance level with target pairs and was used for all predictions in the present paper. For the individual targets in target pairs (red and green curves in Figs. 5, 9, 13, and 16), however, this calculation would be incorrect; each target should be identified with the probability $p\ (t)$, and thus with the same accuracy as a single target irrespective of whether a second target is present or not. (The probability that a particular die shows an, e.g. 6, is independent of the total number of dice you are throwing.) It is interesting, however, that individual targets in NEAR or MIDDLE pairs never reached the same accuracy as single targets; only in FAR distance conditions were the individual targets of target pairs equally well identified as single targets. This underlines that only in the FAR target conditions (and also in the *different* hemifield conditions of Exp.5 and 5a) did targets not disturb each other. Instead of the probability model, however, one might think of other models to explain the reduced performance with double targets. For example, if we assume that the visual system can evaluate only one target at a time and has to switch between targets when more targets must be identified, a time-sharing algorithm might be used for predictions. In a very schematic way, the identification rate of double targets at 120 ms presentation time would then be given by the identification rate of (two) single targets at 60 ms presentation time. However, such an algorithm should, in principle, expand the growing of identification rates, by doubling the time scale, which was not seen in the data.

Eye movements. It is important to briefly discuss the possible effects of eye movements; if subjects had moved their gaze during presentations, data from different conditions might be incomparable. Fortunately, eye movements have not played an important role in the experiments. First, observers were asked to look continuously to the central fixation point on the screen (which was continuously shown during each trial). Controls with a video camera on the observers' eyes confirmed that they followed that instruction. All observers had quickly learned to identify cued targets without moving their eyes. Second, potential gaze shifts guided by the cues would have reached most targets long after they had been masked (Fischer *et al.*, 1983) and should thus have been counterproductive in these tests. Only at certain presentations of "difficult" targets (which generally required longer presentation times to be identified) observers could have used gaze shifts to focus a target, but many of these targets (though not all) were already identified at shorter presentation times for which guided eye movements had not been possible (< 200 ms). The possible advantage of gaze shifts would be even less obvious with double targets. While NEAR targets might have been (nearly) foveated in the same saccade, FAR targets should have required two saccades one after the other to bring both targets near to the fovea. This would predict that the performance with FAR distances should have been worse than the performance with NEAR target pairs ─ opposite to what was found.

Distance vs. hemifield effects.
Instead, the data present evidence for strong interactions between targets in some, and less so in other conditions. While Experiments 1-4 had revealed strong interactions between targets that were located close together, Experiment 5 showed that the distance between targets might be negligible and instead the location of targets in *same* or *different* hemifields was important. Given the limited testing with target configurations as in Experiment 5, however, I would yet hesitate to exclude the influence of distance variations entirely. At least for MIDDLE target conditions, in which the *same* and *different* hemifields conditions could be distinguished in Experiments 1-4, a distance effect might not be rejected completely. In the following I will discuss evidence and possible mechanisms of both effects.

Evidence for distance effects. Interactions between targets in the focus of attention were reported in a number of studies. Intriligator and Cavanagh (2001) showed that the *resolution of the focus of attention* is limited; when targets are presented too closely together, their discrimination is disturbed. This is exactly what was observed in Experiments 1-4 in the present study. According to Intriligator & Cavanagh, however, the size of the attentional focus varies with eccentricity and resolution should be diminished when targets are placed farther away from the fixation point. Given the variation of target locations in NEAR and MIDDLE conditions (Fig.3), target eccentricities varied between 1.8 deg (one raster width from the fixation point) and 6.5 deg (three columns aside and two rows up or down); in this range of eccentricities, resolution variations should not have been so dramatic as observed here. According to their data obtained from endogenous attention shifts (e.g., their Fig.12), the closest pairs in the present study (NEAR, with target spacings of 2.5 deg) should have been well resolved within that range of eccentricities. The authors discuss several other studies on this issue, but although there is a large range of variations, the target distances tested here lay generally far above the attentional resolution limits (and even farther above the spatial resolution limit) at these eccentricities. Thus, the limited resolution of focal attention is unlikely an explanation why the identification of NEAR target pairs was so strongly disturbed. It is also important to realize that the limited resolution of focal attention measured by Intriligator and Cavanagh (2001) is not identical with the exogenously *cued selection* of targets discussed above. Below the attentional resolution limit observers cannot voluntarily select one of two neighboring targets and individually attend to it. As I have already argued above, however, cued selection was very unlikely a limiting factor in the present experiments. Occurrence of the cue had a strong selection effect and made the targets strongly individuated items in a pattern, which observers could easily segregate and, for example, count and locate. But they often failed to correctly report their individual properties when targets were located closely together. This may indeed be caused by limited attentional resolution but not in the selection process.

Another potentially related phenomenon is *crowding*. When neighboring items in a pattern are getting too close, even clearly selected targets may not reliably be distinguished and correctly be identified (Bouma, 1970; Levi, 2008; Strasburger, Rentschler, & Jüttner, 2011). But crowding effects are already seen with single cued targets (e.g., Nothdurft, 2017a) and cannot explain why cued double targets (often with non-cued background items between) should be less correctly identified than a cued single target in the same raster; all these targets are similarly surrounded by nearby items. Sparser item arrangements in a wider raster might have likely improved target identification rates (Nothdurft, 2017a), but similarly for single targets and target pairs in NEAR, MIDDLE and FAR distances.

The reduced identification of target pairs compared to single targets in Experiments 1-4 could be also related to the variable *size of the according attentional focus* (often referred to as the "spotlight" of attention). In the spatial-gradient based "zoom lens" model (Eriksen & St. James, 1986; see also Downing & Pinker, 1985; Shulman, Wilson, & Sheehy, 1985; Shulman, Sheehy, & Wilson, 1986; Henderson & MacQuistan, 1993) small cues evoke faster (and more accurate) responses than large cues (see also Benso, Turatto, Mascetti, & Umiltá, 1998). This would imply that a single target (with a single, small cue) should produce a faster response, and hence a better identification rate at short presentation times, than a NEAR double target with an altogether larger cued area. If the attentional enhancement of neural representations is spread over a larger area, details of the (double) target should be less precisely identified. This might explain why also the identification of individual targets in target pairs is strongly reduced in NEAR target conditions (compare the red and green data curves in, e.g., Fig.5, NEAR with the black curves from single target conditions). The interpretation assumes however, that double cues do not stimulate multiple spotlights of attention but basically one enlarged activation gradient. With larger distances, this gradient should be further enlarged, and the target identification rates be further reduced. How would this then explain the, in fact, better performance with target pairs at FAR distances?

Evidence for hemifield differences. The easiest explanation would be that FAR target pairs are identified in parallel, by separate processes. Remember that FAR target pairs in Experiments 1-4 were always presented in different visual hemifields. The processing of visual information in different hemifields is strictly split into the two hemispheres of the brain, each of which is analyzing information from one visual hemifield only (with a small overlap of the central midline between hemifields which is likely represented in both hemispheres). Double targets presented in different hemifields should then be encoded in different visual areas in the left and right hemispheres. Cued target selection and an attentional enhancements like in the gradient model might be achieved in both hemispheres in parallel, with no disturbing interactions yet at the early processing levels in areas V1.

Several observations in the present work support the model of parallel processing in different hemispheres. First, Experiment 5 clearly showed that the identification of double targets presented in different hemifields (and thus encoded in separate hemispheres) produced little or no interactions between targets even when the target distances were NEAR. On the other hand, targets presented in the same hemifield (and thus encoded in only one hemisphere) showed large interactions irrespective of the target distance and also with FAR target spacings (Fig.19b). Second, individual targets in target pairs were identified (almost) as good as single targets when they were presented in different hemifields (Fig.5 FAR; compare the green, red, and black curves) but not when they were presented in same hemifields (Fig.5 NEAR). On the first view, this might be astonishing. If observers fail to identify all single targets at a given presentation time (black curves, performance rates < 1.0), how could they then equally well identify either one of *two* targets in a target pair, at the same presentation time? The only possibility to achieve similarly good performance with single targets and the individual targets of target pairs would be that cued selection and target identification are to some extent performed in parallel, by two independent processes. (The probability to identify *both* targets of a pair together, $p(t_1 \cap t_2) = p(t_1) \cdot p(t_2)$, should still be reduced, as shown with the gray lines in Figure 5.) When the selection and identification of multiple targets was not achieved from parallel and independent processes, as in the *same* hemifield conditions, the identification of individual targets in target pairs should also be reduced compared to the identification of single targets. This is seen with NEAR target pairs in, e.g., Figures 5 and 16 (red and green curves lie far below the black curves).

There has been cumulating evidence for parallel attentive processing in visual hemifields and different hemispheres of the brain, mainly from studies on the tracking of multiple targets. Alvarez and Cavanagh (2005) reported that twice as many targets could be tracked if targets were presented in different compared to same hemifields. In a later study, Alvarez and colleagues (Alvarez, Gill, & Cavanagh, 2012) expanded this finding to visual search and reported that the search among items within a hemifield required longer reaction times than search for items distributed across hemifields. Holcombe, Chen, and Howe (2014) also found absent long-range interactions in contrast to strong interactions in the target's crowding zone, which would be better explained by hemisphere-specific resource theories than spatial interference. Since attentional modulation is already seen in single cells of area V1 (e.g., Saalmann, Pigarev, & Vidyasagar, 2007) and dynamic properties of cued visual selection can be explained by response properties in early processing levels (Nothdurft, 2017a, b), it is likely that selected target properties can be encoded and transferred from both hemispheres in parallel, before the information is finally brought together and weighed across the entire visual field. This would explain why individual targets of target pairs in different hemifields can be as accurately identified as single targets and why the simultaneous identification of double targets would only be reduced as expected for combined probabilities.

Comment

The design of experiments in this study has changed from merely distance to distance & hemifield aspects. The new target configurations in Experiments 5 and 5a revealed that the major effect in the discrimination of double targets is their distribution across hemifields, and not their distance from each other. It may seem weird to present the findings from Experiments 1-4 which had been designed for distance measurements. But these experiments did not only provide important information about other tested targets, but because of their smaller complexity they also allowed us to look at certain aspects that might have exaggerated the analysis with Experiment 5. For example, the identification of individual targets in target pairs, in comparison to single targets, was not shown and not further discussed in Experiment 5; it would have included altogether six different conditions (NEAR, MIDDLE, FAR distances, each in *same* and *different* hemifields). The important hemifield parameters could also be distinguished in the early experiments, Experiments 1-4; targets at NEAR distances were always presented in same, targets at FAR distances always in different hemifield.

REFERENCES

Alvarez, G. A., & Cavanagh, P. (2005). Independent resources for attentional tracking in the left and right visual hemifields. *Psychological Science, 16* (8), 637–643.

Alvarez, G. A., & Franconeri, S. L. (2007). How many objects can you track?: Evidence for a resource-limited attentive tracking mechanism. *Journal of Vision, 7(13):14,* 1–10, http://journalofvision.org/7/13/14/, doi:10.1167/7.13.14.

Alvarez, G. A., Gill, J., & Cavanagh, P. (2012). Anatomical constraints on attention: Hemifield independence is a signature of multifocal spatial selection. *Journal of Vision, 12(5):9,* 1–20, http://www.journalofvision.org/content/12/5/9, doi:10.1167/12.5.9.

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

Braun, J., & Sagi, D. (1990). Vision outside the focus of attention. Perception & Psychophysics, *48* (1), 45–58.

Benso, F., Turatto, M., Mascetti, G. G. & Umiltá, C. (1998). *The time course of attentional focusing. European Journal of Cognitive Psychology, 10,* 373–388. doi: 10.1080/713752283

Bichot, N. P., Cave, K. R., & Pashler, H. (1999). Visual selection mediated by location: Feature-based selection of noncontiguous locations. *Perception & Psychophysics, 61* (3), 403–423. doi: 10.3758/bf03211962

Bouma, M. (1970). Interaction effects in parafoveal letter recognition. *Nature, 226,* 177–178. doi:10.1038/226177a0

Chakravarthi, R., & VanRullen, R. (2011). Bullet trains and steam engines: Exogenous attention zips but endogenous attention chugs along. *Journal of Vision, 11(4):12,* 1–12, http://www.journalofvision.org/content/11/4/12, doi:10.1167/11.4.12.

Cheal, M. L., & Lyon, D. R. (1992). Benefits from attention depend on the target type in location-precued discrimination. *Acta Psychologica, 81,* 243–267.

Cheal, M. L., & Lyon, D. R. (1994). Allocation of attention in texture segregation, visual search and location-precuing paradigms. *The Quarterly Journal of Experimental Psychology, 47A* (4), 49–70.

de-Wit, L. H., Cole, G. G., Kentridge, R. W., & Milner, A. D. (2011). The parallel representation of the objects selected by attention. *Journal of Vision, 11(4):13,* 1–10, http://www.journalofvision.org/content/11/4/13, doi:10.1167/11.4.13.

Downing, C. J., & Pinker, S. (1985). The spatial structure of visual attention. In: M.I. Posner and O.S.M. Marin (eds.), *Mechanisms of attention: Attention and performance XI* (pp. 171–187). Hillsdale, NJ: Erlbaum.

Dubois, J., Hamker, F. H., & VanRullen, R. (2009). Attentional selection of noncontiguous locations: The spotlight is only transiently "split". *Journal of Vision, 9(5):3,* 1–11, http://journalofvision.org/9/5/3/, doi:10.1167/9.5.3.

Eriksen, C. W., & Colegate, R. L. (1971). Selective attention and serial processing in briefly presented visual displays. *Perception & Psychophysics, 10* (5), 321–326.

Eriksen, C. W., & Hoffman. J. E. (1972). Some characteristics of selective attention in visual perception determined by vocal reaction time. *Perception & Psychophysics, 11* (2), 169–171.

Eriksen, C. W., & Hoffman, J. E. (1973). The extent of processing of noise elements during selective encoding from visual displays. *Perception & Psychophysics, 14* (1), 155–160.

Eriksen, C. W., & St. James, J. D. (1986). Visual attention within and around the field of focal attention: a zoom lens model. *Perception & Psychophysics, 40* (4), 225–240.

Eriksen, C. W., & Yeh, Y. Y. (1985). Allocation of attention in the visual field. *Journal of Experimental Psychology: Human Perception and Performance, 11(5),* 583–597.

Fischer, B., Weber, H., Biscaldi, M., Aiple, F., Otto, P., & Stuhr, V. (1993). Separate populations of visually guided saccades in humans – reaction times and amplitudes. *Experimental Brain Research, 92,* 528–541.

Franconeri, S. L., Alvarez, G. A., & Enns, J. T. (2007). How many locations can be selected at once? *Journal of Experimental Psychology: Human Perception and Performance, 33* (5), 1003–1012. https://doi.org/10.1037/0096-1523.33.5.1003

Gao, D., Mahadevan, V., & Vasconcelos, N. (2008). On the plausibility of the discriminant center-surround hypothesis for visual saliency. *Journal of Vision, 8(7):13,* 1–18, http://journalofvision.org/8/7/13/, doi: 10.1167/8.7.13.

Henderson, J. M., & MacQuistan, A. D. (1993). The spatial distribution of attention following an exogenous cue. *Perception & Psychophysics, 53* (2), *221–230.*

Holcombe, A., and Chen, W.-Y. (2013). Splitting attention reduces temporal resolution from 7 Hz for tracking one object to <3 Hz when tracking three. *Journal of Vision, 13(1):12,* 1–19, http://www.journalofvision.org/content/13/1/12, doi:10.1167/13.1.12.

Holcombe, A. O., Chen, W.-Y., & Howe, P. D. L. (2014). Object tracking: Absence of long-range spatial interference supports resource theories. *Journal of Vision, 14(6):1,* 1–21, http://www.journalofvision.org/content/14/6/1, doi:10.1167/14.6.1.

Intriligator, J., & Cavanagh, P. (2001). The spatial resolution of visual attention. *Cognitive Psychology, 43,* 171–216. doi: 10.1006/cogp.2001.0755.

Inverso, M., Sun, P., Chubb, C., Wright, C. E., & Sperling, G. (2016). Evidence against global attention filters selective for absolute bar-orientation in human vision. *Attention, Perception, & Psychophysics, 78,* 293–308. doi: 10.3758/s13414-015-1005-3

Itthipuripat, S., Garcia. J. O., & Serences, J. T. (2013). Temporal dynamics of divided spatial attention. *Journal of Neurophysiology, 109,* 2364–2373. doi:10.1152/jn.01051.2012.

Jefferies, L. N., & Di Lollo, V. (2015). When can spatial attention be deployed in the form of an annulus? *Attention, Perception, & Psychophysics 77,* 413–422. doi: 10.3758/s13414-014-0790-4

Jonides, J. (1981). Voluntary versus automatic control over the mind's eye. In: J. Long & A. Baddeley (Eds.) *Attention and performance IX* (pp. 187–203). Hillsdale, NJ: Erlbaum.

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

Joseph, J. S., & Optican, L. M. (1996). Involuntary attentional shifts due to orientation differences. *Perception and Psychophysics, 58,* 651–665.

Kamkar, S., Moghaddam, H. A., & Lashgari, R.(2018). Early visual processing of feature saliency tasks: a review of psychophysical experiments. *Frontiers in System Neuroscience, 12:54,* 1–15. doi: 10.3389/fnsys.2018.00054.

Kröse, B. J. A., & Julesz, B. (1989). The control and speed of shifts of attention. *Vision Research, 29* (11), 1607–1619.

Levi, D. M. (2008). Crowding—An essential bottleneck for object recognition: a mini-review. *Vision Research, 48,* 635–654.

Merkel, C., Hopf, J. M., & Schoenfeld, M. A. (2017). Spatio-temporal dynamics of attentional selection stages during multiple object tracking. *NeuroImage, 146,* 484-491.

Moutoussis, K., & Zeki, S. (1997). Functional segregation and temporal hierarchy of the visual perceptive systems. *Proceedings of the Royal Society of London B, 264,* 1407–1414.

Müller, H. J., & Rabbit, P. M. A. (1989). Reflexive and voluntary orienting of visual attention: time course of activation and resistance to interruption. *Journal of Experimental Psychology: Human Perception and Performance, 15* (2), 315–330.

Nakayama, K., & Mackeben, M. (1989). Sustained and transient components of focal visual attention. *Vision Research, 29* (11), 1631–1647.

Nothdurft, H. C. (1999). Focal attention in visual search. *Vision Research, 39,* 2305–2310.

Nothdurft, H. C. (1992). Feature analysis and the role of similarity in pre-attentive vision. *Perception and Psychophysics, 52,* 355–375.

Nothdurft, H. C. (1999). Focal attention in visual search. Vision Research, 39, 2305–2310.

Nothdurft, H.C. (2000). Salience from feature contrast: temporal properties of saliency mechanisms. *Vision Research, 40,* 2421–2435.

Nothdurft, H. C. (2002). Attention shifts to salient targets. *Vision Research, 42,* 1287–1306.

Nothdurft, H. C. (2006). Salience and target selection in visual search. *Visual Cognition, 14* (4-8), 514–542.

Nothdurft, H. C. (2016). Spatial cue effects in Visual Selection. *VPL-reports, 4,* 1–21. www.vpl-reports.de/4/

Nothdurft, H. C. (2017a). Cued visual selection – a tool to study the dynamics of neural processes in perception? *VPL-reports, 6,* 1–24. www.vpl-reports.de/6/

Nothdurft, H. C. (2017b). Cued visual selection of targets with and without orientation contrast. *VPL-reports, 7,* 1–22. www.vpl-reports.de/7/

Nothdurft, H.C. (2018a). Cued visual selection in binocular rivalry. *VPL-reports, 8,* 1–32. www.vpl-reports.de/8/

Nothdurft, H. C. (2018b). Time window(s) of cued visual selection. *VPL-reports, 9,* 1–31. www.vpl-reports.de/9/

Nothdurft, H. C. (2019). Location-cued visual selection — placeholder dots improve target identification. *Journal of Vision, 19(13):16,* 1–15, https://doi.org/10.1167/19.13.16.

Nothdurft, H. C. (2020). Cued visual selection of conjunction targets — no evidence of additional attentional requirements for the binding of color and orientation. *VPL-reports, 11,* 1–14. www.vpl-reports.de/11/

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32,* 3–25.

Posner, M. I., & Cohen, Y. (1984). Components of visual orienting. In: Bouma, H. & Bowhuis, D. (Eds.) *Attention & Performance X (*pp. 531–556), Hillsdale, N.J.: Erlbaum.

Pylyshyn, Z. (1989). The role of location indexes in spatial perception: **A** sketch of the FINST spatial-index model. *Cognition, 32* (1), 65–97.

Pylyshyn, Z. W., & Storm, R. W. (1988). Tracking multiple independent targets: Evidence for a parallel tracking mechanism. *Spatial Vision, 3* (3), 179–197.

Saalmann, Y. B., Pigarev, I. N., & Vidyasagar, T. R. (2007). Neural mechanisms of visual attention: How top-down feedback highlights relevant locations. *Science, 316,* 1612–1615.

Sagi, D., & Julesz, B. (1985). "Where" and "what" in vision. *Science, 228,* 1217–1219.

Sagi, D., & Julesz, B. (1986). Enhanced detection in the aperture of focal attention during simple discrimination tasks. *Nature, 321,* 693–695.

Scialfa, C. T. and Joffe, K. M. (1995). Preferential processing of target features in texture segmentation. *Perception & Psychophysics, 57* (8), 1201–1208.

Shulman, G. L., Wilson, J., & Sheehy, J. B. (1985). Spatial determinants of the distribution of attention. *Perception & Psychophysics, 37* (1), 59–65.

Shulman, G. L., Sheehy, J. B., & Wilson, J. (1986). Gradients of spatial attention. *Acta Psychologica, 61,* 167–181.

Strasburger, H., Rentschler, I., & Jüttner, M. (2011). Peripheral vision and pattern recognition: a review. *Journal of Vision, 11(5):13,* 1–82, http://www.journalofvision.org/content/11/5/13, doi:10.1167/11.5.13.

Theeuwes, J., Kramer, A. F., & Atchley, P. (1999). Attentional effects on preattentive vision: Spatial precues affect the detection of simple features. *Journal of Experimental Psychology: Human Perception and Performance, 25* (2), 341–347.

Treisman, A. (1985). Preattentive processing in vision. *Computer Vision, Graphics and Image Processing, 31,* 156–177.

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology, 12,* 97–136.

Treisman, A., & Schmidt, H. (1982). Illusory conjunctions in the perception of objects. *Cognitive Psychology, 14,* 107–141.

Turatto, M., Benso, F., Facoetti, A., Galfano, G., Mascetti, G., & Umiltá, C. (2000). Automatic and voluntary focusing of attention. *Perception & Psychophysics, 62* (5), 935–952.

Wolfe, J.M. (1998). Visual search. In: Pashler, H. (Ed.) *Attention.* pp.13–73. Hove, UK: Psychology Press.

Wolfe, J. M., Cave, K. R., & Franzel, S. L. (1989). Guided search: An alternative to the feature integration model for visual search. *Journal of Experimental Psychology: Human Perception and Performance, 15,* 419–433.

Wolfe, J. M. (1994). Guided Search 2.0: a revised model of visual search. *Psychonomic Bulletin & Review, 1,* 202–238.

Yantis, S. (1992). Multielement visual tracking - attention and perceptual organization. *Cognitive Psychology 24* (3), 295–340.

Yantis, S., & Jonides, J. (1990). Abrupt visual onsets and selective attention: Voluntary versus automatic allocation. *Journal of Experimental Psychology: Human Perception and Performance, 16* (1), 121–134.