Cued visual selection – a tool to study the dynamics of neural processes in perception?

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Cued visual selection is the (cued) picking of a single item from a crowd. Earlier studies on visual search have shown that salient items are quickly detected and identified, independent of whether salience is generated from feature contrast or from additional salience markers ("cues") that attract focal attention. The present paper measured the dynamics of cuing effects in arrays of oriented lines. Cues were shown at various delays before (Exp. 1) or after (Exp. 2) line pattern onset. In all cases, the cue marked the location of one item (the "target") the orientation of which had then to be identified. Variations of presentation time until the pattern was masked revealed interesting modulations of target visibility. When cues were presented before the target (the standard cuing paradigm, Exp. 1), performance in target identification was highest at short delays between cue and target onset, and then continuously diminished as the delay increased. Variations with target eccentricity were mainly due to crowding (Exp. 1b). However, when lines were onset first and cues later superimposed (Exp. 2), target identification rates were strongly modulated with the cue delay, reflecting the typical time course of a transient neural response after line pattern onset. Target identification was fast when cues were shown 100-400ms after stimulus onset (when transient responses peak) and slowed down at longer cue delays (when responses were attenuated). This suggests that cued visual selection might be a useful tool to look at the dynamics of ongoing neural activity in the brain. *© Author*

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INTRODUCTION

During the last 20 years, the important role of salience in pattern recognition and visual search has become increasingly evident. Experiments in visual search have studied the ability and the speed of observers to detect specific targets that were searched for, but also the ability to simply detect targets that differ from other items nearby and thus may perceptually „stand out". While many earlier studies had underlined a presumably distinctive role of attention in fast and slow visual search (Julesz, 1984; Treisman, 1985; Braun, 1994; Braun & Julesz, 1998), it has meanwhile been shown that fast and slow visual search can be explained with target salience (Nothdurft, 2006a, b; Zehetleitner, Krummenacher, & Müller, 2009; Liesefeld, Moran, Usher, Müller, & Zehetleitner, 2016). Only when targets need to be identified, or distinguished from other salient (non-target) items, analysis requires additional, capacity-limited resources of the visual system, often referred to as „attention" (Sagi & Julesz, 1985; Joseph, Chun, & Nakayama, 1997; Nothdurft, 1999; Theeuwes, Kramer, & Atchley, 1999). The need for attention can be high or low, depending on target salience, difficulty of the task and on the distinctness of targets and non-targets (cf. Nothdurft, 2006a; Chan & Hayward 2014). Salience can attract attention to the target (Itti & Koch, 2000; Turatto *et al.*, 2000; Zenon, Ben Hamed, Duhamel, & Olivier, 2008; cf. Treue, 2003, and Nothdurft, 2006b), but may also distract attention to other salient items (Huang & Pashler, 2005; Koch, Müller, & Zehetleitner, 2013; Liesefeld, Liesefeld, Töllner, & Müller, 2017).

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The analysis of salience is also helpful to predict gaze shifts and visually controlled pointing movements (Parkhurst, Law, & Niebur, 2002; Beutter, Eckstein, & Stone, 2003; Carmi & Itti, 2006; Mulckhuyse, van Zoest, & Theeuwes, 2008; Zehetleitner; Hegenloh, & Müller, 2011; Borji, Sihite, & Itti, 2013; Koehler, Guo, Zhang, & Eckstein, 2014) including disturbances from salient distractors (van Zoest & Donk, 2005; Findlay & Blythe, 2009; van Zoest & Kerzel, 2015; Laidlaw, Zhu, & Kingstone, 2016; Gaspelin, Leonard, & Luck, 2017; van Zoest, Heimler, & Pavani, 2017).

In a study on „attention shifts to salient targets“ (Nothdurft, 2002) fifteen years ago, I showed that salient lines in an array are quickly detected and identified. Increased salience was achieved from luminance contrast (target lines were brighter than all other lines in the display) or motion contrast (targets moved in a different direction). But salience was also increased when certain "marker" cues were presented around the target, with similar effects for target detection and identification. Using additional cues had the advantage that salience and target properties could be manipulated independently so that the target did not have to be distinct from the other items in the display to become salient. This allowed me to generate patterns in which potential targets could not yet be identified as target until the cue was shown. In my early experiments, the additional cues were rings of different sizes around the target, and it turned out that small rings immediately surrounding the target were more efficient in cuing attention to the target (leading to faster identification and better identification rates in short target presentations) than large rings surrounding the target in a farer distance (Nothdurft, 2002).

Using cues as attractors for attention has a long tradition in vision research. In the classical studies set off by Posner and colleagues (Posner, 1980) attention was usually directed to one of two locations at which the target was (later) presented. For short delays between the cue and the target (stimulus onset asynchrony, SOA, ≤ 200 ms), subjects reacted faster to targets at cued locations than to targets elsewhere (“non-cued” locations). Interestingly, the effect was reversed for longer delays (SOA ≥ 300ms); reactions to cued targets were then generally slower than reactions to non-cued targets (Posner and Cohen, 1984). This retardation at longer delays was assumed to reflect inhibition that was considered useful to prevent the visual system from shifting attention repetitiously to the same location (or target), and was therefore later named „inhibition of return“ (IOR; cf. Klein, 2000). In subsequent years, both cued attention and IOR were thoroughly studied (for reviews see, e.g., Carrasco 2011; Evans *et al.*, 2011; Klein, 2000; Wang & Klein, 2010).

The paradigm of cued visual selection that I had used fifteen years ago (Nothdurft, 2002) was totally different. In those experiments, the target was already shown before the cue, together with many other items that also might have become targets should they have been cued and selected. Only the occurrence of the cue decided which item the observer had to identify. Reaction time was not a relevant parameter in this paradigm as only cued targets were identified and hence no comparison of cued and non-cued performance could be made. Nevertheless, the dynamics of cued visual selection remained an interesting aspect, since the speed of target identification and, in particular, the needed presentation time *after* the cue during which the target remained visible became important parameters in these studies. For example, the different efficiency of large and small rings around the target (that were *detected* equally well) was measured by varying the target presentation time before it was masked (Nothdurft, 2002). Observers generally required longer presentations to identify a target cued by the large ring; one subject even failed completely. Since rings of different sizes also vary in overall luminance (and since luminance is an effective salience marker; cf. Nothdurft, 2015a), the observed differences between large and small circles might have been caused by various effects, not alone size. In later experiments, I have therefore replaced the ring cues by configurations of small, dot-like squares („four-dot-cues“) around the target. These new cues then allowed me to vary the cue size and its distance from the target without changing its luminance. It became obvious that targets (always presented in the center of the dot configuration) were better and faster identified when the size of the cue was not too big (Nothdurft, 2016a; see discussion there for size effects in cuing). When cues were too small, however, interactions between the cue and the target occurred that deteriorated target identification. While such interactions would likely have been small in many reported *sequential* cuing experiments, they were quite notable in the cued visual selection paradigm, when cues are later added to the pattern and eventually affect target visibility. The strong influence of cue size and position on target identification speed was confirmed in an additional experiment, in which different cues (lines, rectangular brackets, single dots) were applied as target markers. It turned out that the

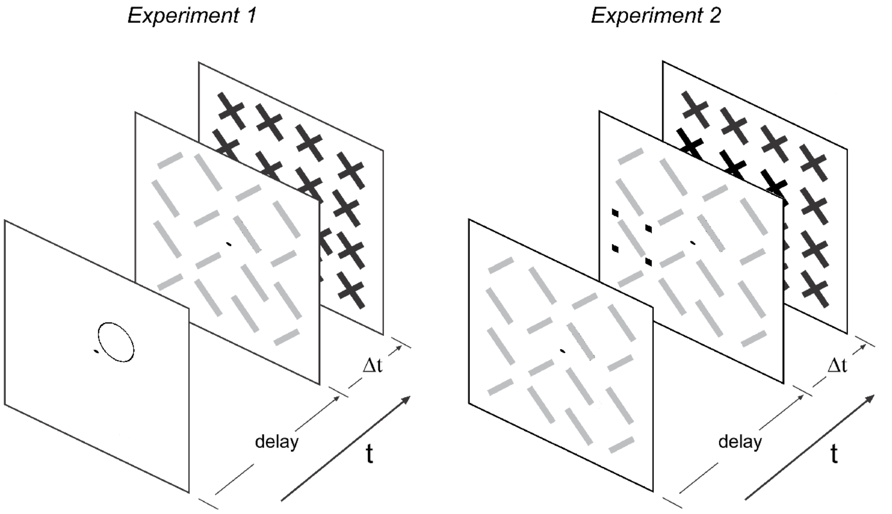

Figure 1. *Schematic Outlines of Experiments 1 and 2* (modified from Nothdurft, 2002). In Experiment 1, the cue (here, a circular annulus) was presented before the test pattern. In Experiment 2, the test pattern was switched on first and the cue (here, four dots) was superimposed *later.* In both experiments, subjects had to indicate the orientation of the cued line ("target"). Cues were shown for 20-33 ms and then switched off. Two parameters were systematically varied in the experiments; the *delay* between cue and test pattern onset (or vice versa) and the *target presentation time, Δt,* measured from the moment when the test pattern was visible and target selection was known, until occurrence of the mask. Note that there were small variations in pattern geometry between the experiments (e.g., no positional jitter in Experiment 2). All experiments were performed under fixation of a central spot on the screen.

speed of target identification was merely controlled by the cue geometry and its distance from the target and that these spatial parameters were predominant even over figural aspects (Nothdurft, 2016b).

The present paper opens a new series of publications that address various dynamic aspects of cued visual selection (CVS). Figure 1 gives an overview of the principle experimental paradigms. It illustrates the difference between the (classical) early cue presentation (Fig. 1a) and the late target selection that can be tested with CVS (Fig. 1b).

GENERAL METHODS

Overview

Test patterns were texture-like arrays of oblique lines which were individually and randomly tilted to the left or right (Fig. 2a). In the course of a trial, one line was cued (thus becoming the target) and the performing observer was asked to identify the tilt of this line by pressing different buttons on a computer keyboard. Mean ratings were obtained from 50-120 repetitions of each test condition. To restrict target analysis time, line patterns were masked after the presentation time. Presentation time (Δt in Fig. 1) was measured from stimulus to mask onset, when the cue was shown before the line pattern (cf. Fig. 1a), or from cue to mask onset, when the line pattern was switched on before the cue (Fig. 1b). Note that in the latter case the true duration of stimulus visibility was longer if the cue was delayed. All subjects could reliably identify the targets from long presentation times but failed when the presentation time was too short; so presentation time, together with the delay between cue and line pattern onsets was systematically varied in the study. The dependent parameter was performance in target identification. While the general task was the same in all experiments of the study, the temporal sequence of cues preceding or following line pattern onset differed between the experiments, and so did, for historical reasons, the form of the cue.

Stimuli

All stimuli were computer generated using standard DOS VGA techniques and displayed on a monitor at a viewing distance of 67 cm; refreshing rates were 60 Hz or 100 Hz (1 Hz = 1 s^{-1}) resulting in a temporal resolution of 16.7 ms and 10 ms, respectively, between subsequent screen display cycles.

Lines were arranged in a 9 x 9 rectangular raster (except in one variant of Experiment 1; see below) with a raster

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width of 1.8 deg. The whole line array covered an area of approximately 15 deg x 15 deg. The center element of the raster was spared and instead a fixation point (0.1 deg x 0.1 deg, green) was shown. Each line could occur at one of two oblique orientations, ±45°; these two orientations were superimposed in the mask (Fig. 2b). There were two versions of stimuli with minor differences between. In version A (used in Exp. 1), lines were 0.9 deg x 0.25 deg and were displayed with a positional jitter of up to ±0.2 deg. In version B (used in Exp. 2), lines were slightly smaller (0.8 deg x 0.2 deg) and were shown without positional jitter. Line orientations and positional jitter (if present) were newly computed in every trial.

Masks were made by superimposing each line in the stimulus pattern with the orthogonal line at the same position so that original line orientations could not further be identified. When the original test pattern had been shown for some time, the sudden onset of orthogonal lines in the mask was sometimes recognized and subjects then made systematically "wrong" responses leading to identification rates well below 50%. However, such "artifacts" occurred only with very short target presentation times after long cue delays and disappeared when target presentation time was long enough so that the subject could identify the target.

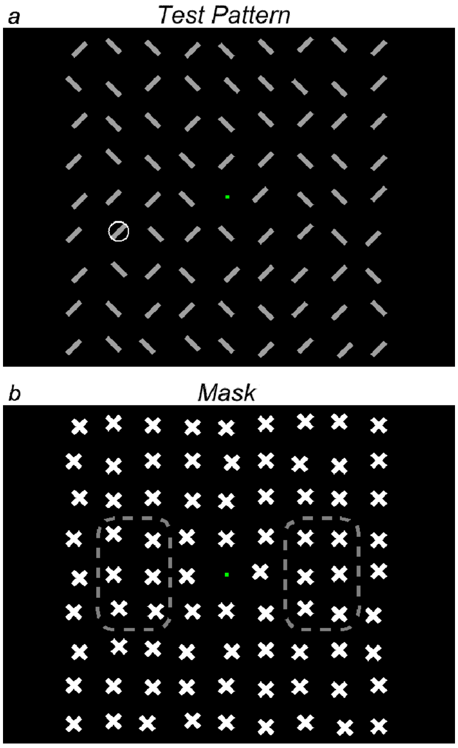

Figure 2. *Stimulus patterns in Experiment 1.* **a.** Example of a test pattern with superimposed cue; **b.** the according mask. Note however, that lines and cues were rarely shown together in the same picture (only at delay 0 ms); in most conditions the cue was presented alone and had disappeared when the test pattern occurred (cf. Fig. 1). Dashed lines in (b) indicate the selected raster positions at which the cue might occur; these lines are only drawn for illustration and were not present in the true stimulus or mask.

The two stimulus versions A and B were also associated with different *cues*. In version A, cues were rings with a diameter of 0.9 deg centered at the actual target location (including shifts from positional jitter) (cf. Fig. 2). In version B, cues were arrangements of four dots ("four-dot cues"), each 0.2 deg x 0.2 deg, which were located in the four oblique directions 0.6 deg from target center (cf. Fig. 7).

Performance varied with target eccentricity. Subjects needed longer presentation times to identify the target when cues were presented at raster positions farther away from the fixation point (like in the next to outermost rows or columns of the raster) than when cues were presented near the fixation point (like in the inner or middle rows and columns; cf. Figs. 5 and 6). To reduce variations but still allow for sufficient variation and unpredictability of cue occurrences, possible *target locations* were restricted to certain raster positions. These restrictions varied between the experiments and will be described there. Subjects were not informed about the restrictions.

All stimuli except the fixation point were white (or gray) on dark background. *Luminance settings* were 10.5 cd/m² for lines, 32 cd/m² for the mask, 62 cd/m² for cues, and 47 cd/m² for the central fixation point (green), all presented on a screen background of about 3 cd/m².

Procedures

Except for one subject in Experiment 1 (mentioned there), all stimuli were viewed binocularly. Each trial started with a 500 ms presentation of the fixation point, before the first stimulus (cue or line pattern) was presented. Cues were shown for 20ms or 33ms depending on monitor frame rate (two video cycles), and then disappeared. Line pattern presentation was terminated with the mask (shown for 500 ms); thereafter the screen was blanked and only the fixation point remained. About 1s after the subject's response, a new trial began. The delay between cue and test pattern and the duration of test pattern presentation were systematically varied.

Subjects who had not been tested with the paradigm before were given several *training sessions* to make them familiar with the task and let them improve their ratings with short target presentation times. At the beginning they were shown typical line patterns and were told that in every trial a single cue would mark one of the lines (or line positions) the orientation (tilt) of which they then had to indicate by pressing either the left-hand "<" key, for tilts to the left, or the right-hand "-" key, for tilts to the right. Even though the task was immediately clear to all subjects, performance was often poor at the very beginning but quickly improved with training. For example, subjects often failed during their first session to identify cued targets in 150ms or 200ms presentations, but could frequently identify targets in 50-100 ms presentations in later sessions. Rating errors were never due to an eventually poor detection of cues but always to difficulties to identify target orientation from short durations. For stable performance ratings, data from the initial sessions were not included in the analysis.

Subjects were not pressed to make fast responses but could take all time they wanted or needed. Trials were grouped in runs, which usually covered all different test conditions of an experiment (delays, in Exp. 1; delays and durations, in Exp. 2), each with 5-20 repetitions; all tests were intermixed in random sequence. Special variations in an experiment were blocked and tested in separate runs (see below). The different runs were repeated 5-10 times, in interleaved sequence, to generate a final data base with at least 30, but usually 50-120 repetitions of every test condition. Experiments were carried out in sessions of 2h each covering several runs. Subjects could pause whenever they wanted.

All tasks in the present study were performed *under fixation*. Subjects were asked to fixate a central point on the screen and not move their eyes before the trial was finished. Stable fixation was controlled for by means of a video camera focused upon the subject's eyes. These controls were frequently made in the first sessions of every subject, and regularly repeated in later sessions. All subjects quickly learned to perform the task without moving their eyes. Furthermore, in most experiments test pattern presentations were too short to let subjects gain any advantages from shifting the gaze towards the cue.

Subjects

Analysis in this paper is based on data from nine subjects (20-34 years old; six female) plus the author (54 years; male). Most subjects were students at the Göttingen University; all were paid for the time they spent in experiment. Subjects had normal or corrected-to normal visual acuity on both eyes and, except the author, were naive as to the aim of the experiments.

RESULTS

All experiments presented here were first attempts to explore the dynamic properties of cued visual selection (CVS). They have revealed interesting observations some of which have meanwhile been further investigated in subsequent studies, and they document some general issues of CVS.

Experiment 1: Cues before the test stimulus – which properties affect target identification?

Regarding the cue-target sequence, the experiment is a modification of the classical cuing paradigm. While observers fixate a central point on the screen, single and briefly presented cues define the location of a (later presented) target that has to be identified. There were, however, important differences to many earlier studies (e.g., Posner, 1980; Posner & Cohen, 1984); (a) targets were not shown alone but were embedded in an array of other lines that all might have served as target if the cue had been differently located; (b) targets had to be identified, not simply detected; (c) hence, correct identification rates, not reaction times were measured as the dependent parameter, and (d) cue-target delays were varied over a much larger range than in many earlier experiments.

Cues were small circles presented closely around the target (Fig. 2) but in most test conditions cues were presented before the line pattern and thus had already disappeared when the target occurred. Only in a few test conditions were cues and targets shown simultaneously (delay 0 ms) or were line patterns presented before the cue (delays < 0 ms). Stimulus presentation time was constant over all test conditions in a run.

Methods

Experiment 1 was performed by five subjects (three female) and the author. Tests were carried out with

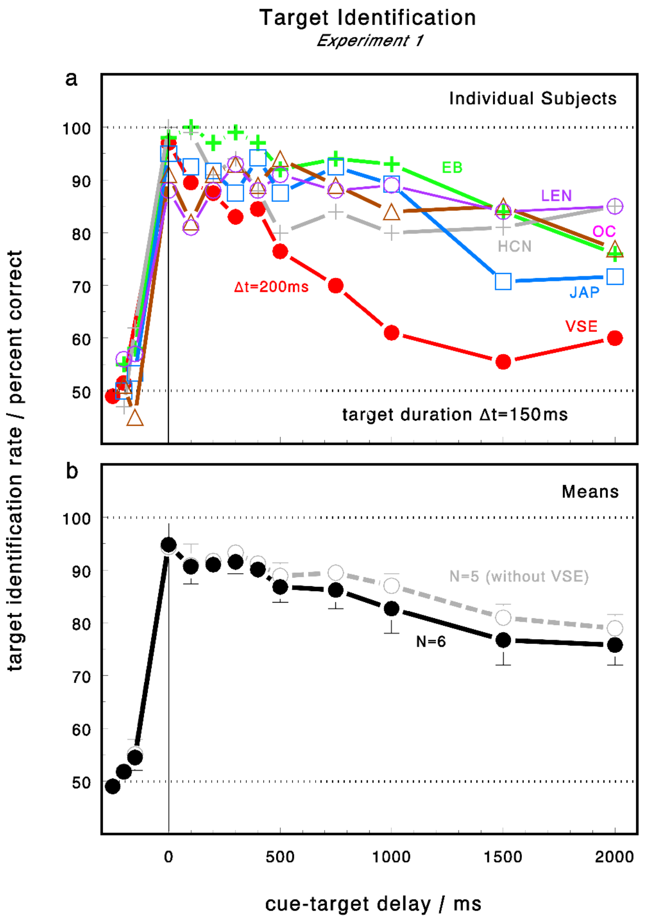

Figure 3. *Target identification in Experiment 1;* ***a.*** *individual observers,* ***b.*** *means (with s.e.m.).* Data points in (a) represent averages of at least 100 responses to each test condition. Target presentation time was constant (Δt=150 ms; Δt=200 ms, for subject VSE). Positive delays give the time between cue and test pattern onset. Two negative delays for cues following the test pattern are shown for comparison. In these conditions, the cue was presented either at mask onset (delays –150 ms and –200 ms, respectively) or 50 ms thereafter (delays –200 ms and –250 ms). With an increasing delay between the cue and the test pattern, target identification rates decreased. In this and subsequent figures, dotted lines indicate the range of valuable ratings between chance performance (50% correct) and perfect target identification (100%).

different frame rates of the monitor (100 Hz and 60 Hz), resulting in slightly different cue durations (20 ms and 33 ms, respectively). All other time settings were identical across the two video frequencies. In most runs of Experiment 1, test pattern duration (Δt in Fig. 1) was 150 ms; in additional runs, also longer and shorter presentations times were tested.

Cue-target delays were systematically varied from 0 ms (cue and line pattern appeared together) to 2000 ms (the line pattern was shown 2 s after the cue). For comparison there were also two "negative" delays in which the line pattern was shown before the cue. One delay was identical to presentation time of the line pattern; that is, the cue appeared at the moment when the line pattern was masked. The other delay was 50 ms longer; i.e., the cue appeared 50 ms after the line pattern had been masked.

Typical test and mask patterns are shown in Figure 2. Possible cue locations were restricted to 12 positions, on the left- and right-hand side from fixation point, in the regions indicated by dashed lines in Figure 2b. Subjects were not informed about these restrictions.

There were two additional modifications of Experiment 1. In one *(Experiment 1a)*, target presentation time was changed. In the second modification *(Experiment 1b)*, the influence of target eccentricity was studied. While in all other tests of Experiment 1, the standard selection of possible target positions was used (Fig. 2b), Experiment 1b distinguished between target positions near and far the fixation point (Fig. 5).

Results

Figure 3 shows correct identification ratings for different delays between cue and the line pattern, at a constant presentation time of 150 ms (except for subject VSE). Whenever the line pattern appeared it was visible for 150 ms and then was masked. For every subject, rating performance was best and often nearly 100% when the line pattern was switched on simultaneously with the cue (delay 0 ms). When the onset of the line pattern was delayed, performance decreased; the strength of this decrease varied between subjects. When the line pattern was shown *before* the cue (cue-target delays < 0ms), identification rates were low and close to chance. This indicates that subjects had not memorized the line pattern and could not recall the (later) cued items from their memories.

There was a minor variation in testing these subjects. Subject VSE had performed the test in an exploratory experiment under monocular viewing conditions; tests with either the left or right eye open were blocked and run in interleaved sequence. Since the ratings from the two eyes were similar, data were averaged for Figure 3. All other subjects had performed the task under binocular viewing conditions. One reason why subject VSE was included here is her particularly strong decay of rating performance with increasing cue-target delays. With delays of 1-2 s, her performance had nearly fallen down to chance. The decays in rating performance of the other subjects were less dramatic but also notable. From nearly 100% correct ratings at cue-target synchrony, their target identification rates fell down to 70-85%. To proof statistical significance of these variations, performance ratings for the delays 0 ms - 400 ms were compared with performance ratings for the delays 500 ms - 2000 ms. In the means and in the individual data of three subjects, these differences were significant (ANOVA, F=16.4, and two-tailed unpaired t-tests; $p<0.005$; one subject, $p<0.05$).

There also was another difference in the tests of VSE. While data from all other subjects were obtained with a presentation time of 150 ms, it had turned out that this duration was too short for subject VSE to obtain high ratings at cue-target synchrony, and a slightly longer target duration was used in her tests. As we will see in Experiment 1a, stimulus presentation time has an important effect on rating performance, and it is likely that subject VSE might have produced similar curves to those of the other subjects when presentation time had been prolonged even further.

To explore the important parameters in CVS, I have tested a number of variants of Experiment 1. Some of these tests revealed particularly interesting and important features of CVS.

Experiment 1a: *Longer and shorter target durations*

Five subjects (all except VSE) repeated Experiment 1 with longer (200 ms or 250 ms), four of them also with shorter line pattern presentation times (100 ms); HCN performed additional runs with 50 ms. Target identification rates generally improved with longer, and generally decreased with shorter presentation times (Fig. 4), but the gradual and continuous decay of performance with increasing cue-target delays remained. For one subject (EB) with already high performance in Experiment 1 (cf. Fig. 3a), the prolongation of presentation time to 250 ms in Experiment 1a did not significantly improve performance. Since she was only tested with longer, not shorter presentation times, her data are not included in Figure 4c. For the remaining four subjects, the overall differences between presentation times were statistically significant (two-factors ANOVA with repetition, F=108.6, $p<0.0001$). Detailed analysis

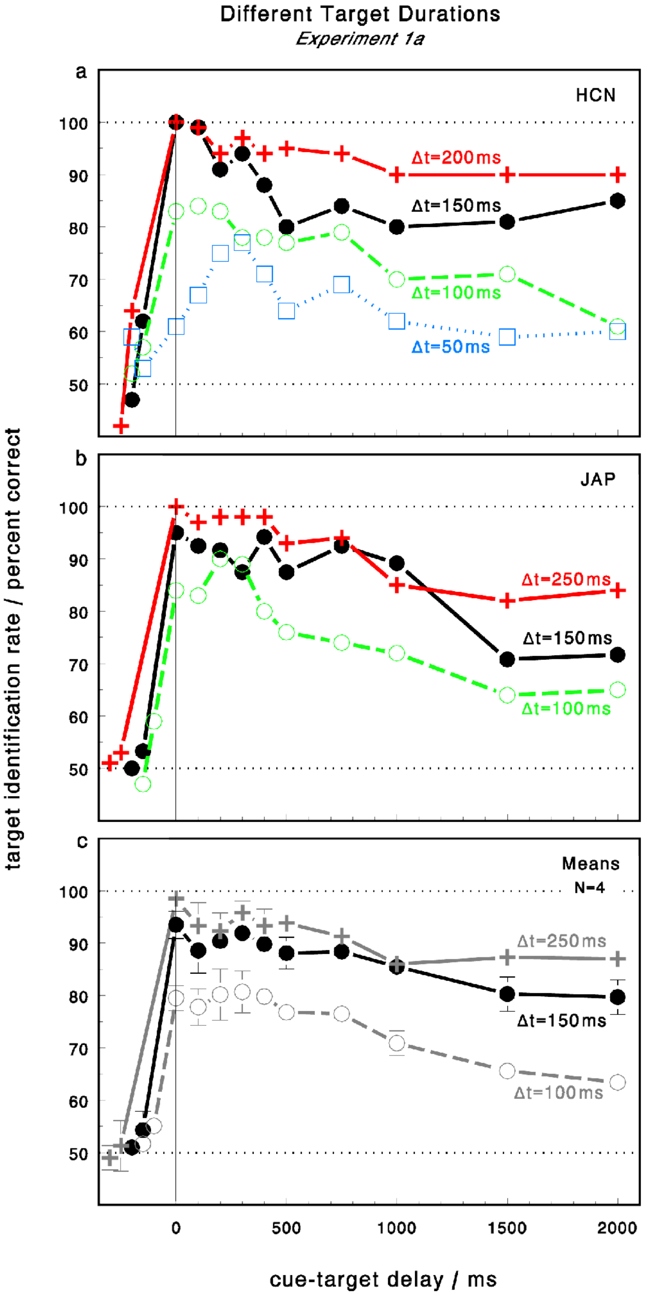

Figure 4. *Experiment 1a: performance variations with target presentation time.* **a.-b.** Examples from individual subjects; **c.** means of all subjects tested with longer (gray, continuous) and shorter target durations (gray, dashed). Performances increased and diminished, respectively, but the general decay of performance with increasing cue-target delays remained.

revealed significant differences between the standard and shorter presentation times for each subject (two-tailed paired t-test, p<0.001; one subject, p<0.005) whereas the improvements with longer presentation times were not always significant (p<0.001, p<0.005, p<0.01, p>0.22, respectively, for the four subjects). Best identification rates were still obtained when cues were presented at test pattern onset (delay 0 ms) or shortly thereafter. When test patterns were shown before the cue (negative cue-target delays), rating performance remained poor even with the long presentation times.

Altogether, the data show that, beyond variations caused from the cue-target delay, target identification rates increase with the duration of line pattern presentations after the cue. Line pattern presentations before the cue could not be used for target analysis.

<u>Experiment 1b:</u> *Variations of target eccentricity*

It has already been noticed in earlier CVS studies (e.g., Nothdurft, 2002, 2016a) that target eccentricity is an important factor in how quickly a cued target can be identified. Targets near the fixation point were faster identified then targets farer away. Even over the small range of eccentricities in the used line raster (1.8 deg to 10.2 deg from the fixation point) performance could differ quite strongly. To reduce these variations, cue and target locations were usually restricted to certain raster positions where differences in rating performance were not too strong (cf. Fig. 2b; eccentricities vary between 3.6 deg and 5.7 deg, with a mean eccentricity of 4.7 deg). So far it has remained unclear whether the visual system would need more time to shift attention to positions farther in the periphery (cf. Benso, Turatto, Mascetti, & Umiltá, 1998; Schade & Meinecke, 2011; but see Remington & Pierce, 1984; Kröse & Julesz, 1989) or whether target analysis there might be slower.

To address the issue experimentally, a second variant of Experiment 1 was designed and tested on five subjects (two female). In separate runs, subjects performed the test with different selections of possible target locations, either "near" or "far" (Fig. 5). Target eccentricities varied from 2.5 deg to 5.4 deg in *near*, and from 5.5 deg to 7.6 deg, in *far* target locations. In addition, there was a "far special" condition in which targets occurred at *far* locations but the raster of the line pattern was halved (and raster width hence doubled). To include the same target locations as tested in the *far* condition, different versions of test patterns had to be used and intermingled, with 4x4, 5x4, and 4x5 rasters, respectively (cf. Fig. 5b). *Near*, *far*, and *far special* conditions were blocked and tested in separate runs, which were interleaved in the course of experiment. Line presentation time was 150 ms.

The differences in rating performance were dramatic (Fig. 6). All subjects performed much better in the *near* conditions (mean target eccentricity 3.7 deg) than in the *far* conditions (mean distance 6.9 deg). But performance strongly improved again in the *far special* condition (where the mean target distance from the fixation point was the same as in *far* but items were arranged more sparsely). Statistically, performance differences between *near* and *far* target conditions were highly significant in the means and all individual subjects (*p<0.0001*, two-tailed paired t-tests; *p<0.0005* for HCN) and not significant at all between *near* and *far special* conditions (*p>0.13*) except for HCN (*p<0.001*), who performed slightly better in the *far special* conditions. On the first

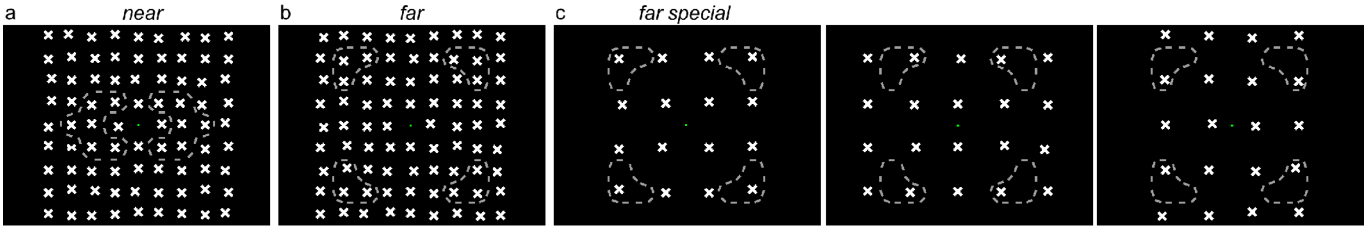

Figure 5. *Target positions tested in Experiment 1b.* **a.-c.** The influence of eccentricity on target identification was measured by restricting cues (and targets), in separate runs, to raster positions *near (a)* or *far (b)* the fixation point. To distinguish distance effects from limited resolution, also a third condition, *far special (c)*, was tested in which target eccentricity was the same as in the *far* condition but line raster was halved (raster width doubled). This special condition required three different patterns to cover the same cue and target locations as the *far* condition. Dashed lines in the mask patterns mark the regions where targets might have occurred; they are only used for illustration and were not shown in experiment.

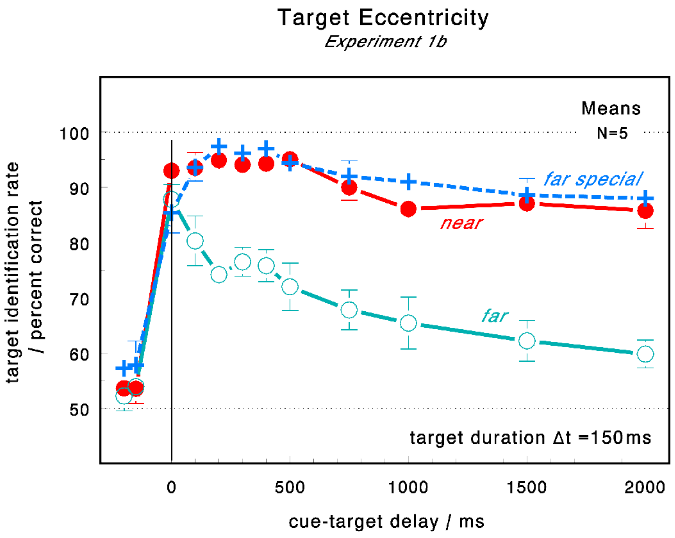

Figure 6. *Experiment 1b: target identification at different eccentricities;* means (and s.e.m.) of five observers. Performance differed strongly between target positions *near* and *far* the fixation point. But when line spacing was increased and crowding effects reduced *(far special)*, even far targets were reliably identified.

glance, these findings suggest that the strong performance variations with target eccentricity are merely due to crowding rather than to temporal differences in salience computation or target analysis between fovea near and more peripheral cue locations.

Discussion

Experiment 1 and its variants 1a and 1b have shown that exogenously cued targets in an array of many different lines can be reliably identified provided the line pattern is shown long enough before it is masked. Patterns were not memorized and thus the identification of targets presented before the cue (and before the target had been selected) was close to chance. The presentation time required for perfect target identification varied between subjects. For most subjects and durations, target identification was best when cues and patterns were shown simultaneously or in rapid succession, and then continuously deteriorated with increasing cue-target delays. With long target durations, performance was generally less strongly modulated than with short durations, but this difference may be due to saturation effects—performance cannot increase beyond 100%.

If we assume that target identification in random and crowded line patterns requires attention and that cues had guided attention to the target (e.g., Nothdurft, 1999, 2002; Turatto *et al.*, 2000; Zenon, Ben Hamed, Duhamel, & Olivier, 2008), then the measured identification rates for a given target duration should directly reflect the amount of attention-based resources deployed to the target. Apparently, this amount diminishes over time so that, after long delays, targets had to be shown for longer durations than after short delays to achieve similar identification rates. In the mean data of all subjects, the decay was continuous, although some individual subjects seemed to have reached various plateaus in performance. One could argue that observers might have "forgotten" the exact cue location after very long delays and were therefore less accurate in selecting the correct line as target. This argument would apparently be supported by the increased performance in the sparse line raster of the *far special* condition in Experiment 1b (Fig. 6). However, the fact that performance with longer target durations was increased, at the same delays (Fig. 4), does not support this interpretation. It seems more plausible to assume a continuous dilution of cued resources over time. The attentional focus should then be still correctly localized but the resources for target analysis might have dissipated. Such dynamics have, in principle, been reported for exogenous cuing (see below).

Comparison with classical cuing experiments.

In the last decades, many properties of cued spatial attention have extensively been studied and described with various metaphors (for an overview see, e.g., Carrasco, 2011). Attention was compared with a spotlight (Posner, 1980; Treisman, 1986) that would illuminate only a small part of a scene but might quickly be shifted to other locations. The size of this spotlight was assumed to be adjustable like a zoom lens (Eriksen & St. James, 1986) to optimize the spatial distribution of attentive resources for a certain stimulus or task. Some of these spatial properties I have already discussed with CVS in one of my earlier studies (Nothdurft, 2016a). The present experiments were mainly interested in temporal aspects of cued visual selection. Apparently, the attentional spotlight (to use this metaphor) must have a built-in dimming mechanism that would make cued attention disperse over time.

Can we compare the present data (e.g., Fig. 3) with data from the original Posner cuing experiment? Posner and Cohen (1984) had found that for short cue-target delays (< 200 ms) reaction times to cued targets were faster than reaction times to non-cued targets. For longer delays (300-500 ms) the differences reversed and reaction times to cued targets were slower than reaction times to non-cued targets. In the CVS paradigm, there are no responses to non-cued targets, and reaction time was not measured in the present study. But assumed that in both experiments cues attract attention to the cued location (which is the common explanation of Posner-like experiments), we should expect faster (better) performance with cue-target delays of up to 200 ms and slower (poorer) performance with cue-target delays of 300-500 ms, where attention effects might have been suppressed. Such a clear incision was not seen in the present data. Ratings were generally high at short cue-target delays and then diminished almost continuously towards longer delays.

It is important to remember that studies on attention have distinguished between exogenously evoked ("bottom-up") attention effects which are transient and limited in time, and endogenously evoked ("top-down") attentional control which is sustained and longer lasting (Weichselgartner & Sperling, 1987; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Yantis & Jonides, 1990; Cheal & Lyon, 1991; Kim & Cave, 1999; Turatto *et al.*, 2000). Cues at target locations (as in the present study) are clearly exogenous but it seems likely that, during the long cue-target delays of up to 2 s, subjects might also have activated endogenous control mechanisms to keep attention at the location where the cue had occurred.

Target eccentricity and crowding

It was already noticed in earlier experiments that target identification at cue locations farther away from the fixation point needed longer presentation times than target identification at cue locations close to the fixation point (cf. Nothdurft, 2002, 2016a). This was confirmed in Experiment 1b. But the experiment has also shown that the performance differences between near and far targets are not due to a potentially different timing of attention effects near or farther away from the fixation point (Benso, Turatto, Mascetti, & Umiltá, 1998) but likely to spatial interaction between the target and neighboring lines (visual crowding). When crowding was reduced, as in the *far special* condition with sparsely arranged items, the identification of targets in the periphery was as fast and as good as the identification of targets near the fixation point. According to Bouma (1970; cited after Strasburger, Rentschler, & Jüttner, 2011), the spatial extent of crowding effects scales with target eccentricity; that is, the strength of crowding with targets at *near* locations (mean eccentricity 3.7 deg) should have almost doubled for targets at *far* locations in the same raster (mean eccentricity 6.9 deg). In fact, Bouma's rule is based on the free space between neighboring lines, which gives a more than doubled spatial extent of crowding effects at the *far* distances (for details, see Strasburger, Rentschler, & Jüttner, 2011). Even doubling the raster width (as in the *far special* conditions) should not have fully compensated for the increased crowding at this eccentricity, but apparently came close to that. The fact that performance in *near* and *far special* target locations was almost identical, indicates that crowding, i.e. spatial interaction, was the predominant source of deterioration with increasing eccentricity. Cue and target sizes had not been changed in these conditions and thus might have been suboptimal at higher eccentricities, but this had no significant effect on performance when crowding effects were removed.

Eye movements

A crucial aspect in Experiment 1 was the suppression of eye movements. If observers had shifted their gaze to the cues, target identification might have been better than without eye movements. Eye movements were controlled for in the initial sessions and from time to time also in later sessions. All subjects had quickly adopted the experimental situation and identified targets without looking there; thus, we can be quite confident that they had not moved their eyes. There is additional evidence from the data. If subjects would have moved their eyes and had looked at the cued locations, performance should have *improved* after the gaze shifts, in particular with longer delays. In fact, however, performance was generally best for very short delays (that would be too short for visually evoked gaze shifts to the cued location; Fischer, 1987; Fischer et al., 1993; see also Nothdurft & Parlitz, 1993), and gradually diminished for longer delays, where gaze shifts (if they had occurred) should have improved performance. Altogether, it thus seems unlikely that data had been falsified by eye movements.

This is even more obvious in the following experiment, where cues were presented late and the target presentation time thereafter was generally too short to gain any advantages from moving the gaze to the target.

Experiment 2: Cues after stimulus onset

One of the challenging aspects of cued visual selection is the circumstance that a pattern can be shown long before the selection cue is given. This technique was adopted from studies on visual search and was originally used to study attention shifts caused by different saliency effects (Nothdurft, 2002, 2016a, b). Its major advantage is that cuing (and visual selection) can be separated from target processing in the visual system. If you look at a pattern like that in Figure 7a, you can likely recognize every single line. But it would be interesting to see how fast you can identify a line after it was cued and suddenly selected as target. You may get an impression of this sort of cued selection from *www.vpl-goettingen.de/cvs/* in the Internet. What are the dynamics of such a process? We make two hypothetical predictions. (1) Since the cuing itself does not differ whether it happens soon after stimulus onset or several seconds later, one might propose that target identification should be the same in both cases. (2) On the other hand, visual processing obviously takes time from shining light upon the retina until the neural representation of a percept; this process could virtually start when the stimulus is shown. Later cuing (and target selection) might then be advantageous; target identification might be particularly fast if it could work on already preprocessed visual information. As Experiment 2 will show, neither of these hypotheses is fully correct.

Preliminary tests using constant target presentation times as in Experiment 1, revealed, on the first glance, similar performance variations with different delays; high performance at or soon after stimulus onset, decreased performance at longer cue delays (cues now followed stimulus onset). On the second glance, however, there were important differences that encouraged me to run an expanded set of test conditions. For each cuing delay, several target durations were now tested. In addition, the ring cue from Experiment 1 was replaced by a four-dot cue (Fig. 7a) which was found to minimize the interference of superimposed cues with target visibility (Nothdurft, 2016a).

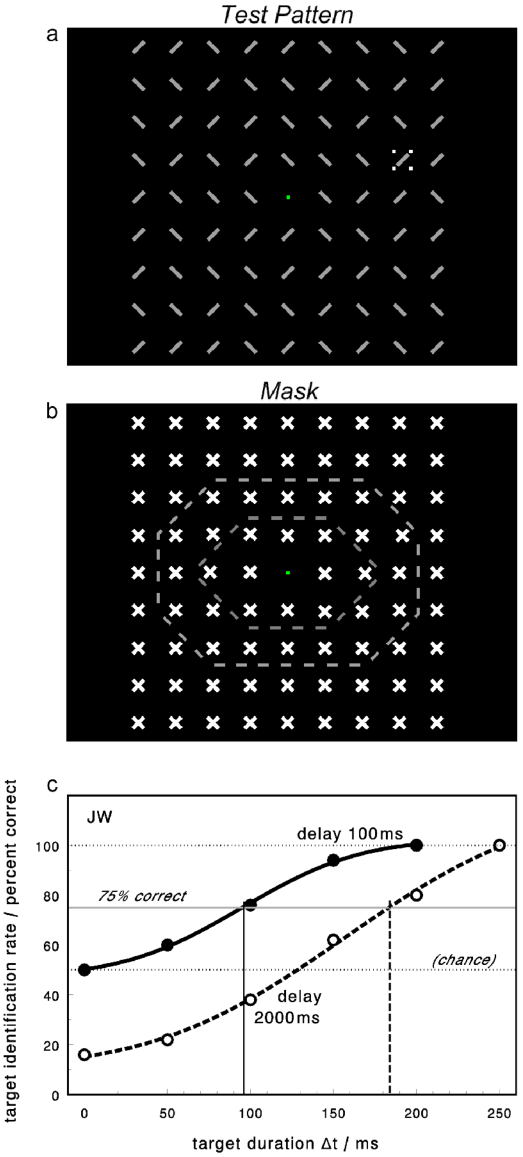

Figure 7. *Introduction to Experiment 2; **a.** example of test pattern with cue; **b.** mask with possible target locations; **c.** fits of two data sets (subject JW) with cumulative functions.* Cue and raster geometry varied slightly from Experiment 1. Test patterns were now presented first, and the cue was (later) superimposed (cf. Fig. 1). Dashed lines in (b) indicate possible cue and target locations; these lines were not visible in experiment and are only shown for illustration. The entire area inside the outer dashed line served as standard set of possible target locations in Experiment 2. For subject JW, however, this area had to be reduced to obtain fast performance and reliable data (smaller region surrounded by dimmer dashed line). The curves in (c) illustrate the analysis typically performed on data sets from Experiment 2. Ratings for various target durations (Δt) at a given cue delay (here plotted for 100 ms, filled circles, and 2000 ms, open circles) were fitted with Gaussian cumulative functions to calculate the target presentation time, Δt_{75}, at which ratings were 75% correct. Data points represent averages from 50 repetitions each; the theoretical standard errors were $\leq 1\%$ and smaller than the symbols.

Delays in Experiment 2 measure the time interval between the (earlier) test pattern onset and the (later) presentation of the cue (Fig. 1). Target duration, Δt, refers to the time period between cue onset and the mask, when observers knew which line they had to identify. The stimulus pattern itself was visible for a longer time period including the delay before the cue.

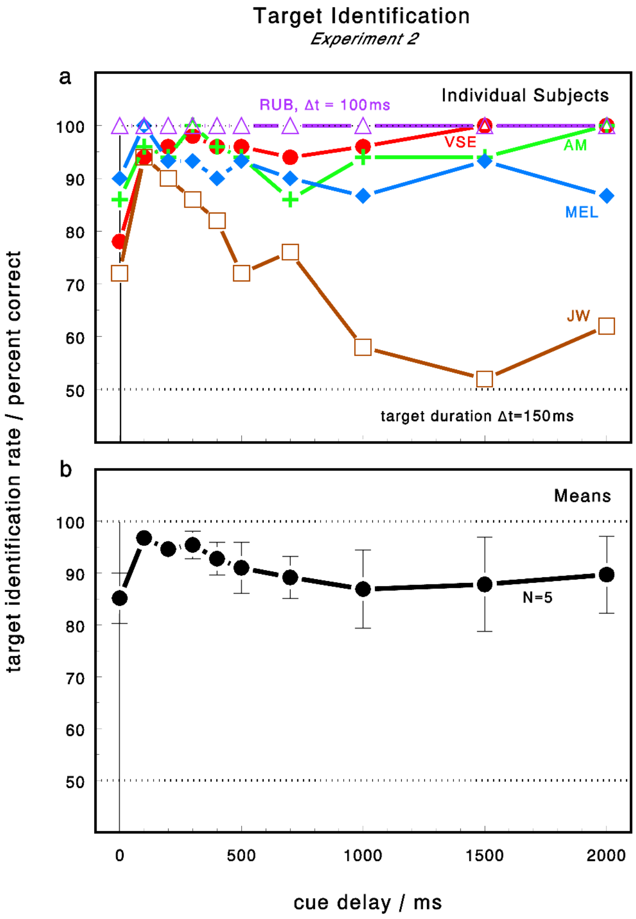

Figure 8. *Target identification in Experiment 2; **a.** individual observers, **b.** means* (with s.e.m.). Test patterns are now presented first (always at 0 ms) and delays measure the time until occurrence of the later presented cue. Data points in (a) represent the average of 50 responses to each delay; target presentation time was Δt=150 ms, except for RUB (Δt=100 ms; 20 responses per data point). Note the similarity and differences to Figure 3. Performance was generally better in Experiment 2. Except for subject JW, target identification rates decreased only little with increasing cue delays, and subject RUB had already reached 100% correct at all delays, with a presentation time of only 100 ms. The only observer tested in both experiments was VSE (red curves); her ratings here were better than in Experiment 1, even though target presentation time was shorter.

Methods

Ten cue delays, between 0 ms and 2 s after stimulus onset, were studied. At each delay, target durations were systematically varied, usually from 0 ms to 150 ms in steps of 30 ms; one subject was tested with larger time steps over a wider range of stimulus durations (50 ms; 0-200 ms) and one with finer steps at a smaller range (10 ms and 20 ms; 0-100 ms). Goal of the experiment was to measure performance variations over different target durations at each tested cue delay.

Note that test series also included zero durations, indicating that targets were masked at the moment when the cue occurred and hence might not be identified. However, to understand rating performances in these conditions, it is important to recall that, with positive non-zero delays, targets had been visible before but not yet identified as target.

Full test series in Experiment 2 covered 60-68 different conditions, depending on the necessary range of target durations to reach reliable performance ratings. These conditions, each with 5-10 repetitions, were mixed and randomly intermingled in a single run. Runs were repeated several times to obtain reliable performance ratings with 50 repetitions of each test condition (corresponding to a theoretical s.e.m. ≤ 1% on the 0-100% scale of mean rating performance).

Experiment 2 was run by five subjects (4 female) who were paid for the time they spent in experiment. Subjects could pause whenever they wanted.

Also in this experiment, the possible cue and target locations were restricted, as indicated in Figure 7b. The test area was slightly larger than in Experiment 1 and covered 30 raster positions at which the cue might occur. For one subject (JW), this area had to be restrained to ten target locations near the fixation point to obtain reliable target identification rates. Subjects were generally not informed about restrictions of possible cue and target locations.

For further analysis, rating curves were fitted with cumulative Gaussian functions (Fig. 7c).

Results

Figure 8 shows performance data from Experiment 2 in a presentation analogue to that of Experiment 1 (Fig. 3). Target presentation time was 150 ms, as in Experiment 1, but remember that, with non-zero cue delays, targets had already been visible before they were cued. Two differences between Figures 3 and 8 should be emphasized; maximum ratings in Experiment 2 were slightly delayed, and ratings in Experiment 2 were generally higher than in Experiment 1. This is particularly obvious in the performance data of subject VSE.

Maximal ratings in Experiment 2 were obtained when cues were presented shortly after the test pattern (delay 100 ms) and not simultaneously with it. This was different in Experiment 1 where rating performance has often been best for synchronous cue and test pattern presentations (delay 0 ms). Zero delays in both experiments represented the same stimulus condition (except for the different cues, circles vs. four dots). We may thus conclude that rating performance in Experiment 1 increased the closer in time the cue was presented before the test pattern (reversely plotted in Fig. 3) and then further increased in Experiment 2 when cues were presented shortly after test pattern onset (Fig. 8). With longer delays, the performance ratings of most subjects remained relatively high in Figure 8, except for subject JW.

This is visualized in Figure 9, which combines the data from Experiments 1 and 2. Only one subject (VSE) was tested in both experiments (and then even with different target durations and inspection modes); therefore the synopsis is mainly based on the means though collected from different subjects. Black and gray curves show the mean rating data of all tested subjects; if a certain target duration had not been tested with a subject in Experiment 2, performance was inter- or extrapolated from measurements nearby. Curves show the variable performance rates for a test pattern that is always switched on at the mid line in Figure 9 (delay 0 ms) and a cue presented at various delays before and after test pattern onset; the data from Experiment 1 are here plotted, in reversed order, at negative delays. There were two principle differences between test conditions on the left- and right-hand sides of the figure. Data on the left-hand side were obtained with ring cues and constant stimulus presentation times (as indicated); data on the right-hand side were obtained with four-dot cues and same target durations but longer stimulus visibility, as the line pattern was always switched on at 0 ms.

All curves in Figure 9 are asymmetric. Performances rise almost continuously from long negative delays (cues presented before targets) to a maximum at short positive delays (100-300 ms) and then gradually descent again. With further increasing delays, however, performance ratings in Experiment 2 (right-hand side of the figure)

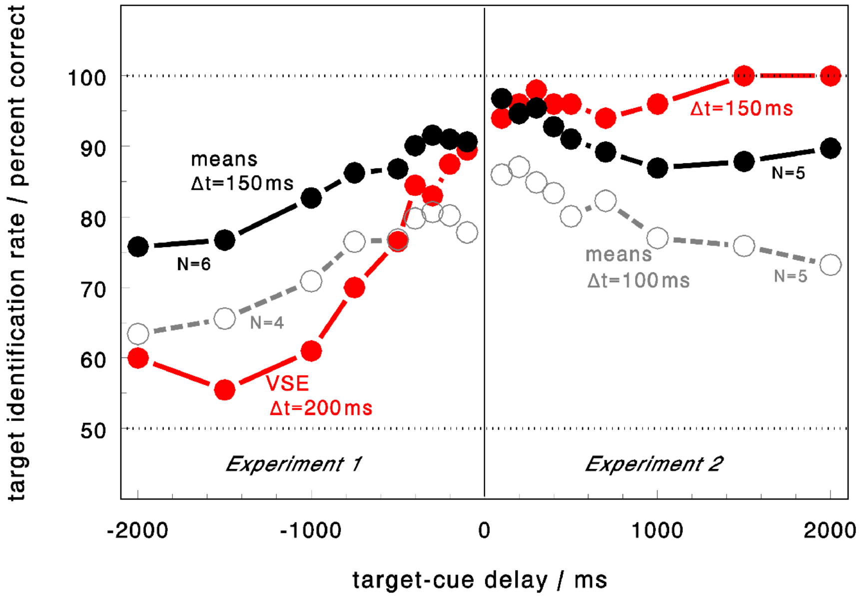

Figure 9. *Synopsis of Experiments 1 and 2.* Replot of performance ratings in Figures 3 and 8. Data from Experiment 1 are now plotted from right to left, starting at zero delay in the middle. In this presentation, the test pattern is always shown at 0 ms delay, performance ratings are plotted at cue onset times before and after that event. Ratings from simultaneous cue and target presentations (delay 0 ms) are omitted because the different cues when superimposed on the line pattern interfered in different strength with target identification. Mean ratings based on up to six (Experiment 1) or five subjects (Experiment 2) are shown for two target durations; ratings from subjects who were not tested at these durations, were interpolated from nearby measures. All performance ratings are asymmetrical; targets in cue-target sequences (Experiment 1) were less correctly identified than targets in test patterns in which the cue was later added (Experiment 2). This is particularly evident for VSE (the only subject who participated in both experiments) who had been tested with even longer target durations in Experiment 1.

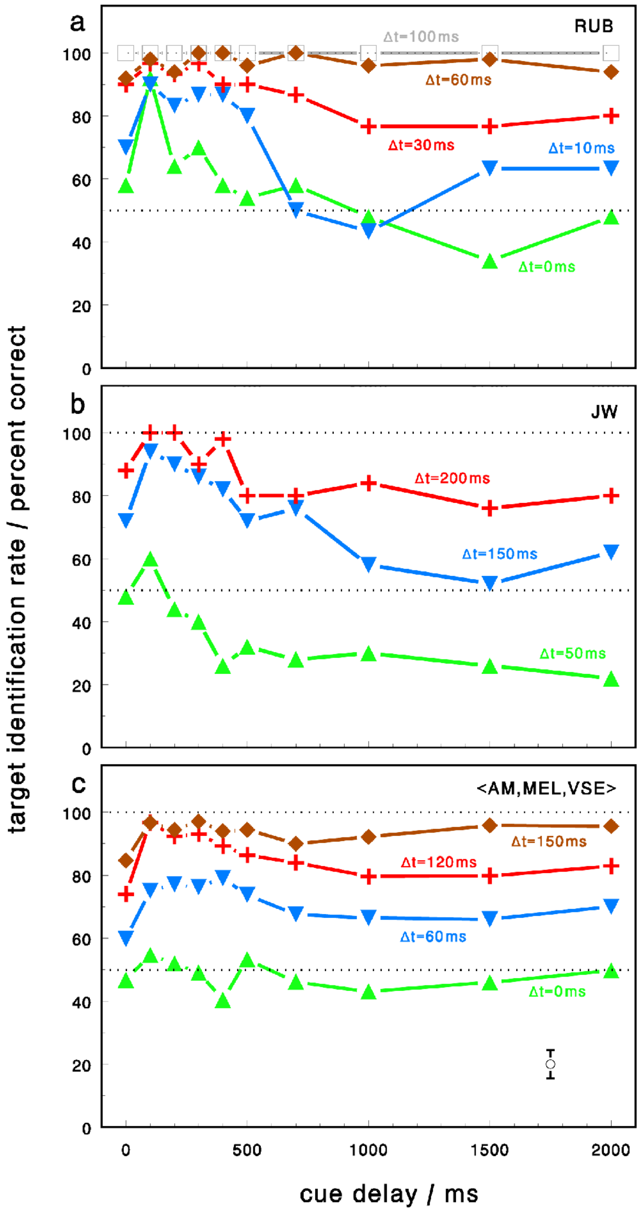

Figure 10. *Performance variations with different target durations in Experiment 2.* **a.-c.** Individual data. Presentation time was systematically varied to cover a wide range of identification ratings at every tested delay. The figure shows selected examples. Two subjects differed from the rest in needing particularly short (a) or particularly long (b) presentation times and were therefore tested with other target durations than the rest. In this and the following figure, data from these two subjects are plotted separately from the means of the remaining three subjects (c). In all three graphs, performance increased with target presentation time, Δt, but increases varied at different delays. For better readability, the s.e.m. of the means in (c) is averaged and plotted as single value.

generally remained higher than those at similar delays in Experiment 1 (left-hand side). There are small inflections at short negative delays, which gowever look stronger here (with the 0 ms data omitted) than in Figures 3 and 4.

It were mainly these differences that had encouraged me to perform a more detailed and extended testing in Experiment 2. For each delay (0-2000 ms) target durations were systematically varied to include performance ratings from 50% to 100%. For three subjects, the standard set of test conditions was sufficient to cover this range; for two other subjects, however, the time settings had to be adjusted. One subject (RUB, 21, male) who was highly experienced from similar tests in another study, was tested with smaller steps over a shorter range of target durations. The other subject (JW, 25, female) needed longer target durations for reliable identification rates, and was tested with coarser time steps over a larger range of target durations.

Performance ratings of these two subjects and mean ratings of the remaining three subjects are shown in Figure 10. They document the generally better performance in Experiment 2 and the peaky character of performance variations over different delays. Despite large differences in the tested target durations, all curves have the same characteristic form. Performance increased at short cue delays (100-500 ms) and then decreased again to lower and finally constant levels at longer delays. This modulation disappears for long target durations when performance was generally improved (cf. RUB, Δt = 60 ms and Δt = 100 ms). Curves from different target durations are not merely shifted but partly compressed in the peak region; that is, targets at short delays were generally better identified than targets at longer cue delays where curves run nearly parallel.

This is better seen when target identification rates are plotted against target duration, at different cue delays (Fig. 11). Several observations in the figure should be emphasized. First, the curves obtained with different cue delays reveal systematic variations that are found in all subjects. With increasing target duration, curves at cue delays 100 ms and 200 ms increase earlier and sometimes more steeply than curves at the 2000 ms delay; the increases with delay 0 ms are often notably flatter and shifted to longer target durations. Second, while most curves start at about 50% (chance performance) with a target duration of 0 ms, quite a few curves start above or below this level. Subject RUB, for example, made 92% correct ratings with zero target duration at the 100 ms cue delay. (As mentioned above, this is not impossible since the target was already visible during the delay time but not yet selected as target.) Performance with zero durations was still improved at the 200 ms delay but not at the much longer 2000 ms delay where the curve started at chance level 50%. Subject JW, on the other hand, had often started at ratings well below 50%, particularly at long delays. This is likely the result of short-term adaptation and the sudden target replacement by the mask. After long delays (during which the target line was visible but not yet labeled as target) the sudden onset of the orthogonal line in the mask was a new and relatively strong stimulus which, in particular with short target presentations after the cue, might then have falsely been identified as target (cf. *www.vpl-goettingen.de/cvs/*). With increasing presentation time, however, the (correct) target signal was enlarged and false recognitions disappeared. This is also seen in Figure 10b; from a certain delay on, the curve obtained with short target presentations ($\Delta t=50$ ms) falls consistently below 50% whereas all ratings on the curve with $\Delta t=150$ ms are better than chance. The strength of this effect should likely depend on the presentation time an observer needs to identify the target, which varied between subjects. According to Figure 11b, JW needed target durations of more than 125 ms to override false target signals from the mask at a cue delay of 2000 ms (i.e., after she had adapted to the target for 2 s). RUB (Fig. 11a), on the other hand, needed at this delay only 10 ms presentation time to identify at least some targets and improve performance above chance. This would explain why false recognitions were absent in his data. The other three subjects (Fig. 11c) could, on average, identify some targets with 30-60 ms duration at this delay.

To gain a better overview of the observed performance variations, rating curves at different cue delays were reduced to one single value, the Δt_{75} duration at which subjects made 75% correct responses, i.e. could correctly identify half of the cued targets. Δt_{75} values were computed from nonlinear fits of cumulative functions (Fig. 7c) to the individual rating data at each delay, and provide a direct measure of an observer's speed to identify targets at this delay. The curves in Figure 12 show the variations of Δt_{75} values over cue delays, for all five subjects. The curves differ in

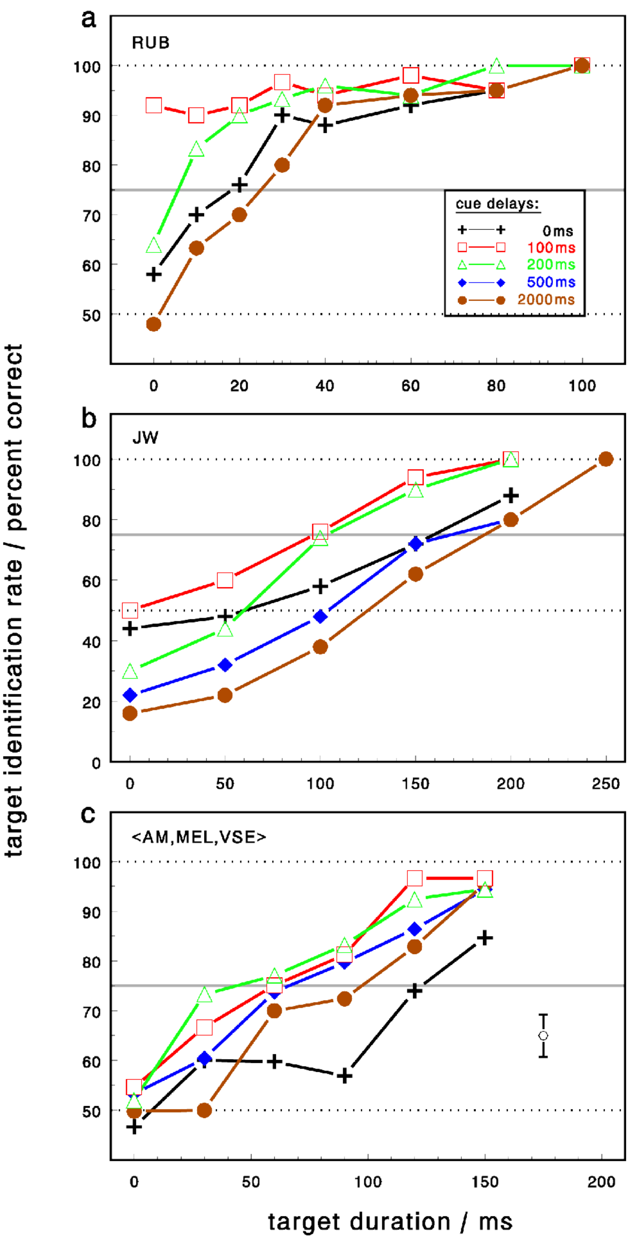

Figure 11. *Performance variations at different cue delays;* ***a-c.*** *same subjects as in Figure 10.* Data are now plotted to show the increase of rating performance with increasing target duration, at selected cue delays. All curves grow from lower to higher levels, when target duration is increased. But there are important differences in the speed of growing for different delays. Curves at delay 0 ms are flatter and reach the 75% level later than, e.g., curves at cue delays 100 ms or 200 ms. Curves at delay 2000 ms again grow more slowly. The relative ranking of curves in (a) and (b) is similar despite the considerable differences in absolute target durations needed by these subjects (note the different scales). For further analysis, data curves as shown here were fitted with Gaussian cumulative functions to find the target duration with 75% correct performance (gray lines), Δt_{75} (cf. Fig. 7c). The s.e.m. of the means in (c) is averaged and plotted as single value.

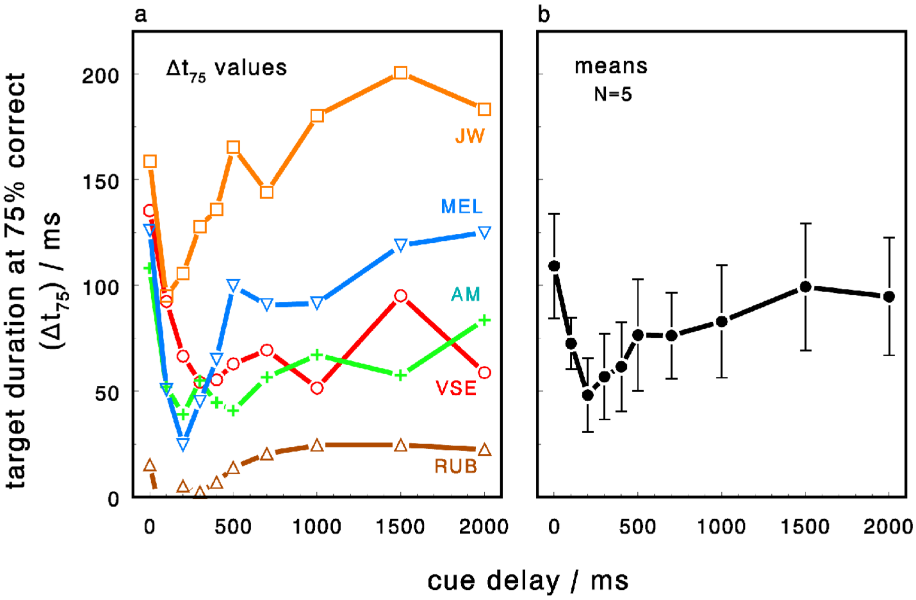

Figure 12. *Δt75 curves; **a.** individual data and **b.** means (with s.e.m.) of all five subjects.* From each performance curve at a given delay, the Δt75 target duration was computed (cf. Fig.7c). Although values differ notably between subjects, there are common modulations. For every subject, the Δt75 values systematically decrease from cue-target synchrony (0 ms) to short delays (100-300 ms) and for most subjects then increase again towards longer delays. Note that no reliable Δt75 value could be computed for subject RUB at delay 100 ms (see text).

absolute values indicating that subjects had individual time settings when they reached 75% correct performance. At zero delay, for example, subject JW needed, on average, 159 ms and subject RUB only 15 ms target presentation time. Despite these differences, however, the curves look similar across subjects; they steeply decline towards cue delays 100 ms and 200 ms and then increase again towards longer cue delays. This later increase was strong in three subjects and less pronounced in subjects AM and VSE. For subject RUB, the *Δt75* value at cue delay 100 ms could not reliably be computed; his ratings at this delay started with 92% correct, for target duration 0 ms (cf. Fig.11a). To obtain a reliable evaluation of *Δt75* at this delay, the data should also include performance ratings at "negative" durations which had however not been tested at this stage of the project. Means of all subjects' data (Fig. 12b) reveal the principle modulation of *Δt75* values; the large s.e.m. reflects the absolute timing differences between subjects. Statistical analysis proved that the differences between *Δt75* values in the delay ranges 100 ms - 400 ms (sample 1) and 700 ms - 2000 ms (sample 2) were significant (2-sided t-tests for non-paired samples with unequal variances; $p<0.01$) in the means and for three individual subjects (not VSE); for subject AM, the differences between delay ranges 100 ms - 500 ms (sample 1) and 700-2000 ms (sample 2) were just significant ($p<0.05$).

Discussion

An important and perhaps unexpected observation from Experiment 2 is that the long stimulus presentations before the cue did, in general, not improve the speed of identification once the target was selected. At certain cue delays, e.g. 100 ms to 400 ms, the required presentation time after the cue was strongly reduced, but at longer delays it was often increased again. That indicates that target properties still had to be evaluated when the cue occurred; the visual system could not make use of the long pattern visibility before the cue. This is surprising. It shows that you may look at a pattern for very long time but cannot identify a later cued target if that does not remain visible after presentation of the cue. The only possibility would be to consciously memorize all items during the long display time before.

The second important observation is that identification rates in CVS were so strongly modulated over the *stimulus* presentation time. After the many studies that have shown that the visibility of a cued target is temporally modulated in synchrony to the *cue*, this finding is surprising, too. The time course of the observed modulation is not synchronized to the cue but to the onset of the stimulus. Depending on how long before the cue the stimulus was switched on, the required presentation time (after the cue) to identify the target could vary strongly. This rejects the two hypotheses we had made before the experiment. Neither was performance constant over all cue delays (first hypothesis) nor did it generally improve the later the cue was shown (second hypothesis). In fact, performance often went down when cues were notably delayed. In the means (Fig. 12b), the shortest *Δt75* value (48 ms) was measured 200 ms after stimulus onset; it was shorter than the *Δt75* value immediately at stimulus onset (109 ms) or 2s later (95 ms). The modulation of target identification speed was seen with all subjects, independent of the presentation time they needed to identify the target (Fig. 12a).

It is interesting to speculate about a possible origin of this modulation. If the visual system had to accumulate neural activity over time to reach a signal that would be strong enough for a reliable decision, then the observed variation of *Δt75* values (which measure this accumulation time) would indicate that the underlying neural signals have varied in strength. They likely were weak at the beginning of the test pattern presentation, thus requiring a long accumulation period, and were particularly strong 100-200 ms later then requiring only short accumulation times for the same reliability. At longer delays (1-2 s), neural signals should have weakened thus requiring longer accumulation times again.

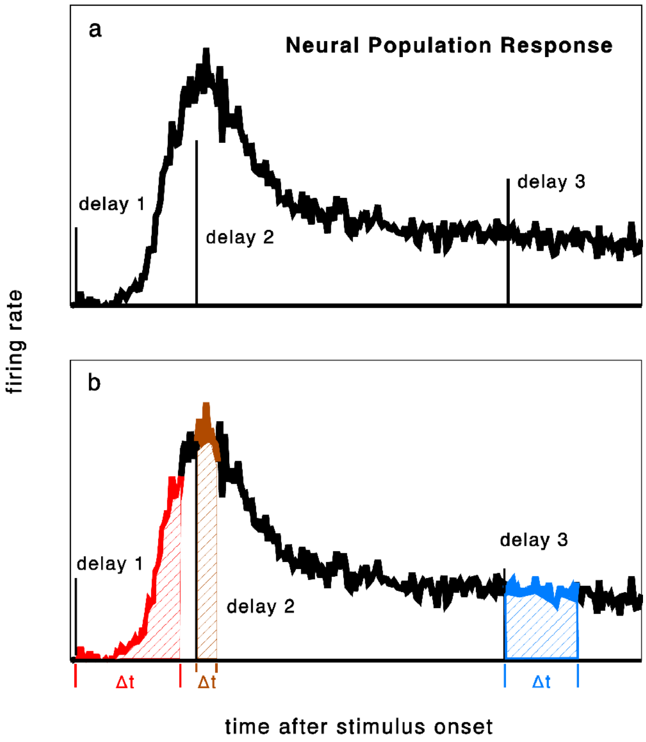

Figure 13. *A hypothetical neural response* illustrates the need of different integration times to achieve signals of similar strength. **a.** Population response of cells in the primary visual cortex (data from Nothdurft, Gallant, & Van Essen, 1999) with three cue delays, for illustration. **b.** Same response pattern with colored sections that represent about the same total amount of neuronal activity. If reliable target identification would require a similarly strong signal, that should be achieved from shorter integration times during the transient response peak (delay 2) than at stimulus onset (delay 1) or later after the peak (delay 3). Although the figure is based on real neuronal data, its intention here is merely the schematic illustration of different accumulation times.

Such a signal is, in principle, very similar to the transient neural responses of cells in many visual areas, and also of cells in the primary visual cortex that encode orientation. The averaged response of a pool of orientation sensitive cortical cells (from Nothdurft, Gallant, & Van Essen, 1999) is schematically plotted in Figure 13, together with the assumed accumulation periods at three delays from stimulus onset. Shortly after stimulus onset (delay 1) the neural response is very small and must be accumulated over a very long time interval to reach sufficient discrimination. During the strong transient firing of the cell population (delay 2), the response is much stronger and a short time interval of response accumulation should be sufficient to achieve a signal of similar strength. Finally, at delays long after stimulus onset (delay 3) the transient response component has vanished and only a smaller level of ongoing neural activity remained. This smaller response (though still larger than the response immediately after pattern onset) should then again require longer response accumulation. In a very schematic approach, we may thus postulate that the time needed to reach a performance level of 75% (the *Δt75* value) at various delays from stimulus onset, should depend on the underlying neural response, *r*, at this delay. If we further assume that the required accumulated signal for a reliable decision is constant, we may write

$$(1) \quad r\,(delay) \cdot \Delta t75\,(delay) = constant$$

and obtain from the known *Δt75* curves in Figure 12 the unknown response curves, *r*,

$$(2) \quad r\,(delay) = constant \,/\, \Delta t75\,(delay)$$

which are plotted (for *constant* = 1) in Figure 14. The curves strongly differ in amplitude (reflecting the large variations of absolute *Δt75* levels) and are plotted at different scales. The different amplitudes are not surprising as the *constant* in equation 1 is not known and might differ between subjects; some subjects needed long, others short target presentations to reach reliable

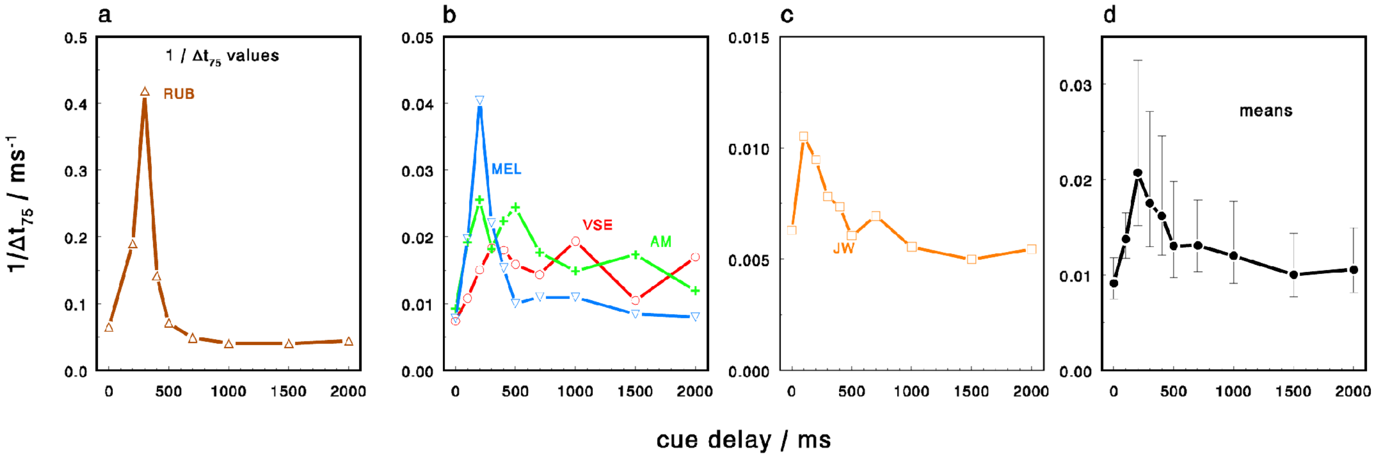

Figure 14. *1/Δt75 transforms of data in Figure 12;* ***a-c.*** *individual subjects and* ***d.*** *transforms of the mean data*. Error bars show the transformed means plus and minus s.e.m., respectively. Curves reveal a coarse reconstruction of the hypothetical neural responses underlying the Δt75 modulations in Figure 12 (see text). The large variations in Figure 12 are enhanced by the transformation and require separate plots to look at the data; cf. different scales in (a-c) and large s.e.m. in (d). Nevertheless, most curves reveal similar characteristics in their individual scales.

performance. The value may also include a subject's experience in a particular task and the individual sensitivity to evaluate and interpret small neuronal signals.

For better readability, the curves in Figures 12 were normalized and replotted in Figure 15 relative to the *Δt75* values at delay 0 ms (set to 100%). The similar modulation across subjects is now obvious, and data of subjects JW and RUB fall closer together than in the original plot (Fig. 12). The s.e.m. of the means is reduced (Fig. 15b). The benefit from normalization is particular strong in the reversed *1/Δt75* plots in Figure 16. The curves of individual observers can now be looked at and compared in one single graph (Fig. 16a), and the s.e.m. is reduced in relation to the strength of the signal (Fig. 16b).

It is important to point out that this very simple approach can only give a broad and inaccurate image of the underlying neural signals. In particular, when *Δt75* values are large and response curves, *r*, vary during the accumulation time, the integration must be performed on dynamic responses that may change during that time. This

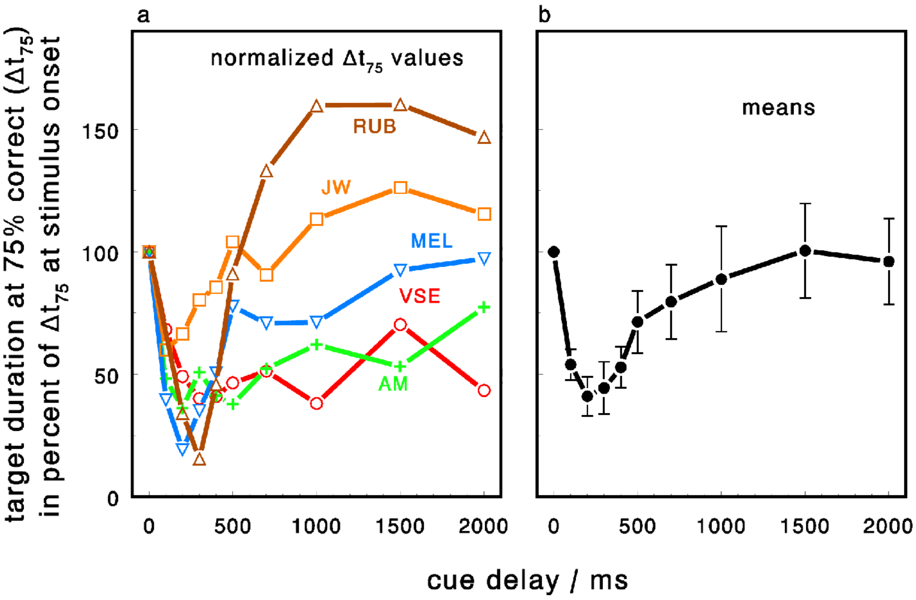

Figure 15. *Normalized Δt75 curves;* ***a.*** *individual data and* ***b.*** *means (with s.e.m.)*. For each subject, data from Figure 12 were rescaled relative to the performance at delay 0 ms (set to 100%). Curves now show the variation of Δt75 relative to the individual levels of target identification speed. The strong differences between subjects JW and RUB in Fig. 12a are collapsed and the s.e.m. of the means is reduced, particularly in the dip of the curve. On average (b), target identification at 200 ms required only 41% of the time needed at stimulus onset (delay 0 ms).

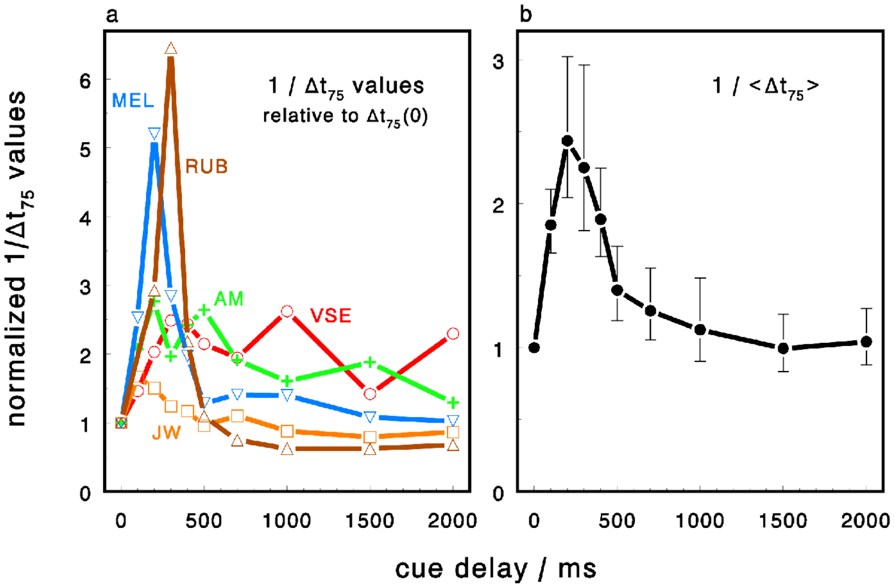

Figure 16. *Relative 1/Δt75 data transforms of the normalized data in Figure 15;* ***a.*** *transformed data from individual subjects;* ***b.*** *transforms of the means with s.e.m. deviations above and below.* Reference data (at delay 0 ms) are set to 1. Curves from different subjects can now be looked at in one scale. In the means (b), the reconstructed neuronal response at delay 200 ms was about 2.5 as large as the reconstructed response at delay 0 ms.

is not taken care of in the above equations and could not be computed from the experimental data of Experiment 2. Furthermore, although the schematic model in Figure 13 is illustrated with data from V1 neurons, the locus of response cumulation remains uncertain.

Nevertheless, the curves in Figure 16 represent plausible (even though "washed-out") trains of neural activity which were derived solely from the performance data in cued visual selection. That *Δt75* values may indeed reflect the dynamics of underlying neural activity, is by and large confirmed in the rating curves of Figure 11. At delay 0 ms, performance of most subjects remained low and only began to increase at relatively long target durations, thus reflecting the latency of the neural response. At short cue delays (100 ms, 200 ms), however, performance curves increased steeply and at short target durations.

The hypothetic model can also explain the observed differences between subjects and the somewhat curious observation that subject RUB could almost perfectly identify targets with zero presentation time at the 100 ms cue delay (Fig. 11). While we do not know the required strength of the accumulated signal to make a subject perform the task correctly, it seems likely that highly trained subjects may have learned to become particularly sensitive to neurons representing the relevant information (here, different line orientations). This would generally reduce their *Δt75* values compared to less experienced and little trained subjects. Beyond that, an experienced observer may still evaluate particularly strong signals when the target is already masked, since the signal from the orthogonal orientation in the mask must accumulate in a similar way from the mask onset before it could effectively mask the (stronger) target signal. This latter effect, the temporarily incomplete compensation of a strong target response by the (delayed) mask response, should, in principle, be found in all subjects, but perhaps only the highly trained and particularly sensitive subjects have been able to make use of it.

Altogether, the data of Experiment 2 suggest, that information obtained with the CVS paradigm reflects the neural stimulus representation at the moment of the cue application. This would provide an elegant and easy way to use the "spotlight of attention" to look at neural representations of various patterns in a highly timed manner.

GENERAL DISCUSSION

Relationship to attention

The paper has studied the dynamic properties of exogenously cued attention in a very specific paradigm. While attention shifts are usually studied with cues presented before target appearance and were often studied with single targets that had to be detected or recognized in cued vs. non-cued conditions, cues in the present study were applied to targets in large arrays and often also to targets that have already been visible for quite a while when the cue occurred. Instead of reaction time, the necessary presentation time to identify the cued target was measured. This does not allow us to distinguish between cued and non-cued conditions but immediately reveals the competitive character of the selection process, which is an intrinsic property of attention. When the cue is applied (and the observer willing to use it as guide in the intended task) then the competition is perfect; only the cued target is selected and perhaps identified – on the cost of all other items in the array that are not identified.

Note that I have tried to avoid the term *attention* for the task performed here. In the past, attention has been used to describe quite different phenomena in vision and visual perception. Attention is the readiness to be prepared for something new or important, and also a mode to not ignore or miss certain information. It is not only something "everyone knows", which is "taking possession of the mind" by "focalisation [and] concentration of consciousness" (James, 1890, p 403; original statement taken from Müller & Krummenacher, 2012) but was also used to explain variations in reaction time (e.g., Posner, 1980) or search performance (e.g., Julesz, 1984; Treisman, 1985), and to measure restrictions from limited processing capacities (Braun, 1994; Nothdurft, 2006a). It is mainly this restriction what seems to be relevant in the context of the present study. When attention is directed to one location, the associated resources are simultaneously not fully available elsewhere (cf. Braun & Sagi, 1991; Braun & Julesz, 1998). Indeed, in the CVS experiments presented here, observers tried to identify the briefly presented cued targets and no other items in the array. The analogy is limited, however, since even with the CVS paradigm it is possible to analyze two or more simultaneously cued targets (Nothdurft, 2006b). Even Titchener's law of prior entry ("the object of attention comes to consciousness more quickly than the objects we are not attending to"; Titchener, 1908; cited after Redden, d'Entremont, & Klein, 2017) is explicitly true in the CVS paradigm; however, temporal differences are irrelevant as only the attended target is identified.

Also the *effects* of directed attention on visual perception are manifold. Attention reduces external noise (Lu, Lesmes, & Dosher, 2002) and makes (attended) items be seen better, with more and clearer details (see Carrasco, 2011, for an overview). It alters the perceived contrast of an item (Carrasco, Ling, & Read, 1994; Cutrone; Heeger, & Carrasco, 2014), improves the spatial resolution and thus an observer's acuity at attended locations (Yeshurun & Carrasco, 1999) on the cost of non-attended locations (Montagna, Pestilli, & Carrasco, 2009). It enhances the sensitivity for texture and 2nd-order contrast (Barbot, Landy, & Carrasco, 2011), improves the temporal discrimination (Chica & Christie, 2009) and appears to prolong the perceived duration of an attended stimulus (Seifried & Ulrich, 2011). Last but not least, it may even make you see something which is not there, like faces in the clouds. However, all these many functions of attention would be of little relevance in the CVS paradigm of the present study. The major advantage of referring to attention here had been its competitive character; only one item was selected for identification. It was this clear task (and the irrelevance of most other manifestations of attention) which suggested me to introduce the term "cued visual selection" instead of attention for the experiments reported here. Cued or voluntary selection of items, objects, or, for example, surfaces (e.g., Valdes-Sosa, Bobes, Rodriguez, & Pinilla, 1998; Reynolds, Alborzian, & Stoner, 2003) is an important aspect of visual perception and visually driven behavior.

Many studies have reported differences in activity between seemingly attending and seemingly non-attending brain regions and cells (see, for example, reviews by Kastner & Ungerleider, 2000, 2001; Treue, 2001; Maunsell & Treue, 2006; Chelazzi, Libera, Sani, & Santandrea, 2011) but so far it has remained unclear how some of these differences arise and how they might control the selection and further visual processing of exclusively one single item, as in the CVS experiments. This uncertainty would be another good reason why to avoid the somewhat unspecific term *attention* here. Nevertheless, CVS experiments did uncover many properties that had already been described in visual attention studies. Cued visual selection (CVS) obviously is an important aspect of attention. It includes the competition and selection of certain stimuli in the visual surrounding and likely also the competition between visual areas and brain regions for further processing and perhaps adequate reactions. It may also include an improved representation of important stimulus details in the brain that have been found in neural studies. However, with the simple task of the present CVS experiments, the improved neural representation would not be the predominant aspect.

Relationship to visual search and salience

The CVS paradigm itself (selection of a target in a crowd) is not new but was frequently used in studies on visual search, in which endogenous (top-down) and exogenous (bottom-up) controls were combined to investigate different manifestations of attentional control (for reviews, see Wolfe & Horrowitz, 2004; Evans *et al.*, 2011). Exogenous cuing was frequently used to select or, in the attention terminology, to direct attention to targets that were searched for. Cues in these studies were often inhomogeneities in the distribution of targets and distractors, like local variations ("singletons") in luminance, color, or certain other feature properties ("feature contrast"; cf. Nothdurft, 1993, 2015b), which have been shown to increase the salience of these items (cf. Gao, Mahadevan, & Vasconcelos, 2008). There are many samples of evidence that salient items attract attention and thus provide fast detection and identification of targets (e.g., Nothdurft, 1999; 2002; 2006a, b; Zenon, Ben Hamed, Duhamel, & Olivier, 2008; Zehetleitner, Krummenacher, & Müller, 2009; Liesefeld, Moran, Usher, Müller, & Zehetleitner, 2016) or notable distraction from targets when other items ("distractors") are also made salient (Huang & Pashler, 2005; van Zoest & Donk, 2005; Mulckhuyse, van Zoest, & Theeuwes, 2008; Zehetleitner, Koch, Goschy, & Müller, 2013; Liesefeld, Liesefeld, Töllner, & Müller, 2017). The usage of separate cues as target "markers" has revealed similar functional properties (Nothdurft, 2002, 2006b). However, cues must fulfill certain requirements not only to select an item but also to allow its identification (Nothdurft, 2016a). Particularly when cues are shown together with the target, as was the case in Experiment 2, they must not spatially interfere and disturb identification. Rings, for example, unless shown before the target, as in Experiment 1, may lead to slower and poorer target identification than luminance or motion contrast applied directly to the target (Nothdurft, 2002).

CONCLUSIONS

The present study has revealed that cues not only attract attention (whatever that is) but may also reveal the temporal characteristics of the underlying stimulus representation in the visual system. When the cue preceded the line pattern, the strength of cuing effects was found to decay in time; best performance was obtained when target and cue were presented together (Experiment 1). With a fixed (target) presentation time, identification could become increasingly difficult when the delay between cue and target increased. When the sequence was reversed and cues were (later) presented in an already visible line pattern (Experiment 2), rating performance varied notably, merely reflecting the typical neuronal response to the target at the time of the cue. This suggests that the CVS paradigm might be particularly useful to study temporal properties of target encoding beyond the dynamics of cuing effects themselves.

These observations are even more promising, as they suggest that the CVS paradigm might be used to unravel temporal properties of processes that are not consciously perceived. If cues direct attention to stimulus properties we are not aware of, maybe CVS could uncover some of them. In a series of experiments following the initial discoveries of the present paper, I have studied the phenomena of contextual modulation in oriented line patterns and other stimuli using the paradigm of cued visual selection.

REFERENCES

Barbot, A., Landy, M.S., & Carrasco, M. (2011). Exogenous attention enhances 2nd-order contrast sensitivity. *Vision Research, 51,* 1086–1098. doi:10.1016/j.visres.2011.02.022

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

Beutter, B.R., Eckstein, M.P., & Stone, L.S. (2003). Saccadic and perceptual performance in visual search tasks. I. Contrast detection and discrimination. *Journal of the Optical Society of America A: Optics, Image Science, and Vision, 20(7),* 1341-1351.

Borji, A., Sihite, D.N., & Itti, L. (2013). What stands out in a scene? A study of human explicit saliency judgment. *Vision Research, 91,* 62-77. http://dx.doi.org/10.1016/j.visres.2013.07.016

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

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

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

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

Carmi, R., & Itti, L. (2006). Visual causes versus correlates of attentional selection in dynamic scenes. *Vision Research, 46,* 4333–4345. doi:10.1016/j.visres.2006.08.019

Carrasco, M. (2011). Visual attention: the past 25 years. *Vision Research, 51,* 1484-1525.

Carrasco, M., Ling, S., & Read, S. (2004). Attention alters appearance. *Nature Neuroscience, 7(3),* 308-313.

Chan. L.K.H., & Hayward, W.G. (2014). No attentional capture for simple visual search: Evidence for a dual-route account. *Journal of Experimental Psychology: Human Perception and Performance, 40(6),* 2154–2166. doi: 10.1037/a0037897

Cheal, M.L. & Lyon, D.R. (1991). Central and peripheral precuing of forced-choice discrimination. *The Quarterly Journal of Experimental Psychology, 43A,* 859-880.

Chelazzi, L., Libera, C.D., Sani, I., & Santandrea, E. (2011). Neural basis of visual selective attention. *Wiley interdisciplinary reviews: Cognitive science, 2,* 392-407. doi: 10.1002/wcs.117

Chica, A.B., & Christie, J. (2009). Spatial attention does improve temporal discrimination. *Attention, Perception, & Psychophysics, 71(2),* 273-280. doi:10.3758/APP.71.2.273

Cutrone, E. K., Heeger, D. J., & Carrasco, M. (2014). Attention enhances contrast appearance via increased input baseline of neural responses. *Journal of Vision, 14(14):16,* 1–14, http://www.journalofvision.org/content/14/14/16, doi:10.1167/14.14.16.

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.

Evans, K.K., Horowitz, T.S., Howe, P., Pedersini, R., Reijnen, E., Pinto, Y., Kuzmova, Y., & Wolfe, J.M. (2011). Visual attention. *Wiley Interdisciplinary Reviews: Cognitive Science, 2,* 503-514.

Findlay, J.M., & Blythe, H.I. (2009). Saccade target selection: Do distractors affect saccade accuracy? *Vision Research, 49,* 1267–1274. doi:10.1016/j.visres.2008.07.005

Fischer, B. (1987). The preparation of visually guided saccades. *Reviews of Physiology Biochemistry and Pharmacology, 106,* 1-35.

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

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.

Gaspelin, N., Leonard, C.J., & Luck, S.J. (2017). Suppression of overt attentional capture by salient-but-irrelevant color singletons. *Attention, Perception, & Psychophysics, 79,* 45–62. doi: 10.3758/s13414-016-1209-1

Huang, L., & Pashler, H. (2005). Quantifying object salience by equating distractor effects. *Vision Research, 45(14),* 1909-1920.

Itti, L., & Koch, C. (2000). A saliency-based search mechanism for overt and covert shifts of visual attention. *Vision Research, 40,* 1489-1506.

James, W. (1890). *The principles of psychology.* Holt, New York.

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

Julesz, B. (1984). Toward an axiomatic theory of preattentive vision. In: Edelman, G.M., Gall, W.E., & Cowan, W.M. (Eds.) *Dynamic aspects of neocortical function*. Neurosciences Research Foundation, Inc., pp. 585-612.

Kastner, S., & Ungerleider, L.G. (2000). Mechanisms of visual attention in the human cortex. *Annual Review of,Neuroscience*, *23,* 315-341.

Kastner, S., & Ungerleider, L.G. (2001). The neural basis of biased competition in human visual cortex. *Neuropsychologia*, *39,* 1263-1276.

Kim, M.-S., & Cave, K.R. (1999). Top-down and bottom-up attentional control: On the nature of interference from a salient distractor. *Perception & Psychophysics, 61(6),* 1009-1023.

Klein, R.M. (2000). Inhibition of return. *Trends in Cognitive Sciences, 4(4),* 138-147. doi: 10.1016/S1364-6613(00)01452-2

Koch, A.I., Müller, H.J., & Zehetleitner, M. (2013). Distractors less salient than targets capture attention rather than producing non-spatial filtering costs. *Acta Psychologica, 144,* 61–72. http://dx.doi.org/10.1016/j.actpsy.2013.04.023

Koehler, K., Guo, F., Zhang, S., & Eckstein, M. P. (2014). What do saliency models predict? *Journal of Vision, 14(3):14,* 1– 27, http://www.journalofvision.org/content/14/3/14, doi:10.1167/14.3.14.

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

Laidlaw, K.E.W., Zhu, M.J.H., & Kingstone, A. (2016). Looking away: distractor influences on saccadic trajectory and endpoint in prosaccade and antisaccade tasks. *Experimental Brain Research, 234,* 1637–1648. doi: 10.1007/s00221-016-4551-6

Liesefeld, H.R., Liesefeld, A.M., Tollner, T., & Müller, H.J. (2017). Attentional capture in visual search: Capture and post-capture dynamics revealed by EEG. *NeuroImage, 156,* 166–173. doi: 10.1016/j.neuroimage.2017.05.016

Liesefeld, H.R, Moran, R., Usher, M., Müller, H.J., & Zehetleitner, M. (2016). Search efficiency as a function of target saliency: The transition from inefficient to efficient search and beyond. *Journal of Experimental Psychology: Human Perception and Performance, 42(6),* 821–836. doi: 10.1037/xhp0000156

Lu, Z.L., Lesmes, L.A., & Dosher, B.A. (2002). Spatial attention excludes external noise at the target location. *Journal of Vision, 2(4):*4. doi: 10.1167/2.4.4.

Maunsell, J.H.R., & Treue, S. (2006). Feature-based attention in visual cortex. *Trends in Neurosciences, 29(6),* 317-322.

Montagna, B., Pestilli, F., & Carrasco, M. (2009). Attention trades off spatial acuity. *Vision Research, 49,* 735–745.

Mulckhuyse, M., van Zoest, W., & Theeuwes, J. (2008). Capture of the eyes by relevant and irrelevant onsets. *Experimental Brain Research, 186,* 225–235, doi: 10.1007/s00221-007-1226-3

Müller, H., Krummenacher, J. (2012). Funktionen und Modelle der selektiven Aufmerksamkeit. In: Karnath, H.O., Thier, P. (Eds) *Kognitive Neurowissenschaften.* Springer-Lehrbuch. Springer, Berlin, Heidelberg, pp. 307-321.doi: 10.1007/978-3-642-25527-4_28

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

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

Nothdurft, H.C. (1993). The role of features in preattentive vision: comparison of orientation, motion, and color cues. *Vision Research, 33,* 1937-1958.

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

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

Nothdurft, H.C. (2006a). Salience-controlled visual search: are the brightest and the least bright targets found by different processes? *Visual Cognition, 13(6),* 700-732.

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

Nothdurft, H.C. (2015a). Luminance-defined salience of homogeneous blob arrays. *VPL-reports, 1,* 1-38. www.vpl-reports.de/1/

Nothdurft, H.C. (2015b). The role of features in salience and grouping: luminance and disparity. VPL-reports, 3, 1-32. www.vpl-reports.de/3/

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

Nothdurft, H.C. (2016b). Fast identification of salient objects depends on cue location. VPL-reports, 5, 1-8. www.vpl-reports.de/5/

Nothdurft, H.C., Gallant, J.L. & Van Essen, D.C. (1999). Response modulation by texture surround in primate area V1: Correlates of "popout" under anesthesia. *Visual Neuroscience*, *16,* 15-34.

Nothdurft, H.C., & Parlitz, D. (1993). Absence of express saccades to texture or motion defined targets. *Vision Reseach, 33(10),* 1367-1383.

Parkhurst, D., Law, K., & Niebur, E. (2002). Modeling the role of salience in the allocation of overt visual attention. *Vision Research, 42,* 107–123.

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*, Hillsdale, N.J.: Erlbaum, 32, pp. 531-556.

Redden, R.S., d'Entremont, G., & Klein, R.M. (2017). Further evidence in favor of prior entry from endogenous attention to a location in space. *Attention, Perception, & Psychophysics, 79,* 1027–1038. doi: 10.3758/s13414-017-1290-0

Remington, R. & Pierce, L. (1984). Moving attention: evidence for time-invariant shifts of visual selective attention. *Perception & Psychophysics*, *35,* 393-399.

Reynolds, J.H., Alborzian, S., & Stoner, G.R. (2003). Exogenously cued attention triggers competitive selection of surfaces. *Vision Research, 43,* 59–66.

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

Schade, U., & Meinecke, C. (2011). Texture segmentation: Do the processing units on the saliency map increase with eccentricity? *Vision Research, 51,* 1–12. doi: 10.1016/j.visres.2010.09.010

Seifried, T., & Ulrich, R. (2011). Exogenous visual attention prolongs perceived duration. *Attention, Perception, & Psychophysics, 73,* 68–85. doi: 10.3758/s13414-010-0005-6

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.

Titchener, E.B. (1908). *Lectures on the elementary psychology of feeling and attention.* New York, NY: Macmillan.

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

Treisman, A. (1986). Features and objects in visual processing. *Scientific American, 255(5),* 106-115.

Treue, S. (2001). Neural correlates of attention in primate visual cortex. *Trends in Neurosciences*, *24,* 295-300.

Treue, S. (2003). Visual attention: the where, what, how and why of saliency. *Current Opinion in Neurobiology, 13,* 428-432.

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.

van Zoest, W., & Donk, M. (2005). The effects of salience on saccadic target selection. *Visual Cognition, 12(2),* 353-375.

van Zoest, W., Heimler, B., & Pavani, F. (2017). The oculomotor salience of flicker, apparent motion and continuous motion in saccade trajectories. *Experimental Brain Research, 235,* 181–191. doi: 10.1007/s00221-016-4779-1

van Zoest, W., & Kerzel, D. (2015). The effects of saliency on manual reach trajectories and reach target selection. *Vision Research, 113,* 179–187. doi: 10.1016/j.visres.2014.11.015

Valdes-Sosa, M., Bobes, M.A., Rodriguez, V., & Pinilla, T. (1998). Switching attention without shifting the spotlight: Object-based attentional modulation of brain potentials. *Journal of Cognitive Neuroscience, 10(1),* 137–151.

Wang, Z.G., & Klein, R.M. (2010). Searching for inhibition of return in visual search: A review. *Vision Research, 50(2),* 220-228. doi: 10.1016/j.visres.2009.11.013

Weichselgartner, E. & Sperling, G. (1987). Dynamics of automatic and controlled visual attention. *Science*, *238,* 778-780.

Wolfe, J.M., & Horowitz, T.S. (2004). What attributes guide the deployment of visual attention and how do they do it? *Nature Reviews Neuroscience, 5,* 1-7.

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.

Yeshurun, Y., & Carrasco, M. (1999). Spatial attention improves performance in spatial resolution tasks. *Vision Research, 39,* 293–306.

Zehetleitner, M., Hegenloh, M., & Müller, H.J. (2011). Visually guided pointing movements are driven by the salience map. *Journal of Vision, 11(1):24,* 1–18, http://www.journalofvision.org/content/11/1/24, doi:10.1167/11.1.24.

Zehetleitner, M., Koch, A.I., Goschy, H., & Müller, H.J. (2013). Salience-based selection: Interference by distractors less salient than the target. *PloS One, 8,* e52595. doi:10.1371/journal.pone.0052595

Zehetleitner, M., Krummenacher, J., & Müller, H.J. (2009). The detection of feature singletons defined in two dimensions is based on salience summation, rather than on serial exhaustive or interactive race architectures. *Attention, Perception, & Psychophysics, 71(8),* 1739-1759. doi: 10.3758/APP.71.8.1739

Zenon, A., Ben Hamed, S., Duhamel, J.R., Olivier, E. (2008) Spatial and temporal dynamics of attentional guidance during inefficient visual search. *PLoS One 3(5), e2219.* doi:10.1371/journal.pone.0002219