Selecting Spatial Frames of Reference for Visual Target Localization

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Abstract. This study examined the selection of spatial frames of reference for target localization in visual search. Participants searched for local target characters in global character configurations. The local targets could be localized relative to the character configuration in which they were embedded or relative to the presentation screen on which the configurations were displayed. We investigated under which conditions the configurations, or the screen served as frame of reference for target localization. Three experiments revealed an increasing impact of screen-related target localization with decreasing spatial uncertainty of targets in screen-related coordinates. The results indicate the capability of the visual system to localize relevant visual stimuli with respect to those frames of reference that yield the most redundant spatial distribution of these stimuli.

Keywords: frames of reference, visual search, spatial coding

Often we know what we are looking for but we don't know its location. For example, we search for signs in an unknown building, for power buttons on technical apparatus, or for an author's name in a book chapter. Finding a searched for object normally means to localize it, and it is widely acknowledged that this localization is accomplished by a (c)overt orientation of visual attention (e.g., Posner, 1980; Schneider, 1995; Treisman & Gelade, 1980; Treisman & Schmidt, 1982; Tsal & Lavie, 1988).

To determine an object's location some spatial frame of reference is necessary (see Corballis, 1988; Hinton & Parsons, 1988, for a formal description of reference frames). For example, a statement like "the chair is located on the left" would be meaningless unless it is specified to which frame of reference the term "left" relates to (e.g., the observer, the outline of the room, another salient reference object like the door or whatever else). Thus, to unambiguously localize an object it is necessary to select one of the various possible spatial frames of reference that a natural visual scene offers.

As long as all available frames are equally predictive of an object's location, it is of little relevance how a location is coded. For example, the location of a nose can be specified equally reliably as "below the eyes," "above the mouth," or "in the middle of the face." If, however, potential frames differ considerably in their predictive power, it is essential to have access to those spatial codes that posses a low variability of the object's location. For example, when driving a car, the location of traffic signs is more predictable in relation to the roadside than, say, the outline of the car's front shield. It is therefore clearly more advantageous that visual search for traffic signs is guided by the frame of reference provided by the roadside rather than by the front shield.

Although this capability to select predictive frames of reference is a tacit assumption in several models of visual cognition (e.g., in models that assume the selection of object-centered frames of reference for the localization of object features, e.g., Biederman, 1987; Hummel & Biederman, 1992; Marr, 1982), it has rarely been explicitly addressed in experimental psychology. Some studies have shown that visual attention can, in principle, adapt to different frames of reference. For example, Robertson (1995) reported that the so-called rightwards directional bias (i.e.,

DOI: 10.1027/1618-3169.52.3.201

faster processing of stimuli in the right than in the left half field) can occur in egocentric as well as allocentric coordinates. Likewise, Tipper, Weaver, Jerrat, and Burak (1994) observed that inhibition of return (i.e., impaired stimulus detection at recently attended locations) can relate to object-based as well as environment-based coordinates (see also Tipper, Jordan, & Weaver, 1999; Umiltà, Castiello, Fontana & Vestri, 1995). Still, little is known about the factors that eventually affect the preference of one reference frame over the other.

In the present study we suggest that visual attention codes the location of target objects relative to those frames of reference that posses a low variability of target objects. We will call this the *uncertainty-reduction* hypothesis. This is a very simple but powerful prediction, and actually confirming it represents a first step in the investigation of the (presumably multiple) factors that affect reference frame selection in the orienting of attention. To test this hypothesis we varied the uncertainty about the location of relevant target objects in one of two possible frames of reference while keeping constant the spatial uncertainty in the other frame. This rationale is described in detail in the following.

Experimental Rationale

How can one know which frame of reference observers use to specify a given stimulus location? Obviously some behavioral measure is needed here. In the following we describe a measure that has turned out to be helpful in a previous study of ours (Hoffmann & Kunde, 1999).

Participants were to search for two targets that were presented in one of the seven positions of a global configuration of distractors (see Figure 1 for examples of such configurations). We will refer to the positions of the configurations by numbering them from left to right consecutively. One target was equiprobable at all positions, whereas the other target was unequally distributed and appeared particularly often in one so-called "critical position." The relevant find-

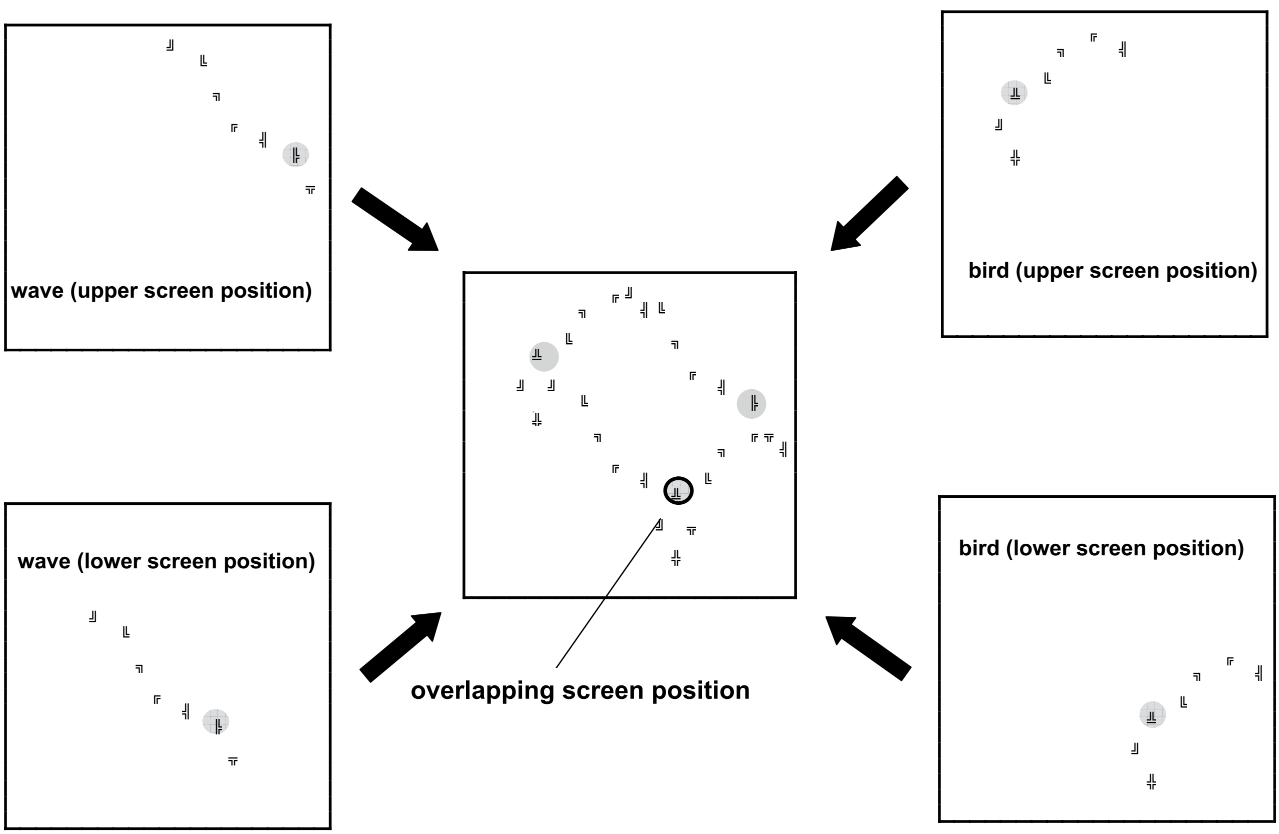

Figure 1. Positioning of the global configurations bird and wave on the screen. Only one of the four depicted configurations was presented in each individual trial. The four outer figures depict sample displays with the stimuli used in Experiment 1 (letters were used in Experiments 2 and 3). Only for the purpose of illustration the critical positions are shaded. The middle figure shows the overlapping screen locations of the bottom wave and bird letter configuration.

ing with such a distribution is that (apart from overall faster responding at the frequent location, see Shaw & Shaw, 1977), in a given position, the particular target that was presented there more frequently is detected more quickly (Hoffmann & Kunde, 1999; Lambert & Hockey, 1986; Miller, 1988).

For example, with the target probabilities in Table 1, target F would be detected faster than target H in position 3, whereas target H would be detected faster than target F in the remaining positions (1–2 and 4–7).

However, each position within a configuration of characters is, at the same time, a location on the screen within which the stimuli are presented. Thus, it is not immediately apparent whether targets are attended at certain configural positions or at certain screen locations. This ambiguity can be resolved by presenting participants with *two* different and clearly discriminable configurations (e.g., a "wave-like" and a "bird-like" configuration), at varying positions on a screen (see Figure 1). To determine the frame of reference two arrangements were made. First, the two configurations were placed so that their respective critical locations used one identical screen location (see the lower presentation position in Figure 1, middle). Second, the unequally distributed target letter of one configuration was the equally distributed target letter in the other configuration, and vice versa. Thus, if the letter F served as unequally distributed target in bird, it served as the equally distributed target in wave. And if the letter H served as the equally distributed target in bird it served as the unequally distributed target in wave.

Table 2 shows that with these arrangements both targets are equally frequent at the overlapping screen location (e.g., H and F occurring in 9.5% + 1.75% = 11.25% of target-present trials in this location, respectively). Different predictions emerge depending on whether the screen or the configurations served as frame of reference. If target locations were specified

Table 1. Relative frequencies of the equally distributed target and the unequally distributed target in the seven positions of the bird configuration (in % of presentations of bird containing a target). Distractors appeared with equal probability in all positions.

	Position							
Target	1	2	3	4	5	6	7	Total (%)
Equally distributed (e.g., H)	7	7	7	7	8	7	7	50
Unequally distributed (e.g., F)	2	2	38	2	2	2	2	50
Total	9	9	45	9	10	9	9	100

Table 2. Relative frequencies of target characters in the overlapping critical position (in % of target-present trials).

Configuration and target	Overlapping critical position
Bird	
H (equally distributed)	1.75
F (unequally distributed)	9.50
Wave	
H (unequally distributed)	9.50
F (equally distributed)	1.75

relative to the screen, no detection differences between the targets should occur, because at these overlapping *screen* position both target were equally frequent. If, however, target locations were specified as *configural* positions, expectancy effects should reflect target frequencies within configurations. Thus, in the overlapping critical position, the configuration's unequally distributed target should be detected more quickly than the equally distributed target irrespective of the overlap on the screen (i.e., in bird, the letter F should be detected more quickly than the H, whereas the opposite should be true in wave). Hence, the performance at the overlapping positions and the comparison with the other nonoverlapping positions provides a measure of the frame of reference applied.

Our main experimental manipulation concerned the predictability of targets at screen locations, while the predictability of targets at configural positions was kept constant. To obtain a quantitative description of this manipulation, one can formally compute an index of uncertainty (called entropy) of targets in screen coordinates and configural coordinates, respectively (see Attneave, 1954).

In information theory the uncertainty about an event is termed entropy. The entropy H of a distribution X of i single events (x) is a function of the probabilities of these single events $p(xi)$. For calculating the entropy of the target distribution in a screen-defined reference system, the probability of appearance of each target in each of the i = 27 possible screen locations (regardless of their position within the global configuration) was considered as $p(xi)$. The entropy of the target distribution was calculated as $H(X) = \sum_{i=1}^{27} p(xi) * log_2 \frac{1}{p(xi)}$. For calculating the entropy of the target distribution within a configural reference system, the probability of each target in each of the i = 7 possible positions of a given configuration (regardless of its screen location) was considered a single event (see Table 1). The entropy of target distribution in bird and wave are identical (only the location of the critical position varied). However, the target probabilities are defined only after the respective configuration has been determined. Because both configurations appeared with a probability of p = .5, this introduces an additional uncertainty of 1 bit. Thus, the entropy of target distribution in the two possible configurations amounts to $H(X) = 1 + \sum_{i=1}^{7} p(xi) * log_2 \frac{1}{p(xi)}$ (see Attneave, 1954). Applying these formulas results in a constant entropy of 4.11 bit for configural coordinates in all three experiments. By contrast the entropy for screen coordinates declines from 4.97 bit in Experiment 1, to 4.54 bit in Experiment 2 and to 3.82 bit in Experiment 3.

We expected that a screen-bound frame of reference would be more likely to be adopted the lower the spatial uncertainty of the targets at its locations (i.e., the higher the predictability of targets at screen locations). We will refer to this as the uncertainty-reduction hypothesis.

Experiment 1

In a recent study that adopted the afore described procedure, we found a preference for configural target localization over screen-bound target localization. Our first step was to replicate this finding with two essential modifications.

First, in our previous study we created global stimulus configurations from letters of the alphabet. It has been suggested that letters are processed by specific letter detection mechanisms, which are especially sensitive to frequency variations of letters in relative positions of global letter configurations (see Miller, 1988). In other words, these letter detection mechanisms per se use a configuration-related coding of target letters. One may therefore argue that the observed preference for a configural target localization, simply resulted from the use of letters as stimuli, rather than from the fact that a configural target localization was more advantageous in terms of spatial target variability, as we claim. Therefore, Experiment 1 tested if the preference of a configural reference frame, still holds if geometrical line patterns are used as stimuli, which by definition rules out influences of specific letter perception mechanisms.

Second, we changed the response mode. Whereas in our previous study participants pressed a different response key for each of the two targets, with always one target being present (*discrimination mode*), we now had them press one response key when either of the two targets was present and another key when both targets were absent (*detection mode*). A potential problem with assigning targets to different manual responses (discrimination mode) is that performance differences between targets might occur at the perceptual level as well as on the response level. Therefore, we found it necessary to test if the preference for configuration-based target coding found in our previous study has to do with the way participants responded to the targets, and hence we used a different response mode here. Also, our uncertainty-reduction hypothesis makes no specific assumption on the type of target response. Replicating our previous result with a different response mode would thus suggest that our disregard of response-related factors in our hypothesis was not a terrible oversimplification.

Except for stimulus material and response mode the spatial target distribution in Experiment 1 replicates that of our previous study (Hoffmann & Kunde, 1999, Exp. 3). The local stimuli were arranged to form two global configurations denoted as bird and wave. The distribution of the two targets within the configurations (see Table 1) and the positioning of the two configurations on the screen remained unaltered (see Figure 1). Therefore, we expected a configuration-bound coding of target locations. Consequently, the respective unequally distributed target of a presented configuration should be detected faster than the equally distributed target in the critical positions, irrespective of whether this position overlapped with the other configuration on the screen or not.

Method

Participants

Sixteen undergraduates (3 men, 13 women) at the University of Würzburg, with normal or corrected to normal vision, aged from 20 to 35 years served as participants in fulfillment of a course requirement. Each participant was tested in a single session lasting about 45 min.

Apparatus and Materials

Stimuli were presented and responses and reaction times (RTs) were recorded by a IBM-compatible PC with a 15-inch VGA Graphics-Display. The viewing distance was approximately 60 cm. The characters appeared in blue color on white background in the cells of an invisible 21 × 21 grid that was 20 cm wide and 18 cm high on the display. They were arranged to form one of two configurations (a bird-like or a wave-like configuration) at one of two screen positions each, resulting in four different figures (see Figure 1). Each of the figures consisted of seven ASCII characters. One figure was presented in each trial. The characters were 6 mm high and 4 mm wide and separated by a center to center distance of 2 cm. The ASCII characters ╩ and ╠ were used as targets, and the characters ╬, ╝, ╚, ╗, ╔, ╣, ╦ served as distractors. Responses were made with the index fingers of the left and right hand on an external response device with response keys separated by about 15 cm. Half the participants pressed the right key when a target was present and the left key when targets were absent. This mapping was reversed for the other half of participants. In the bird as well as in the wave configuration there was one so called critical position in which one target appeared particularly often, whereas the other target was equidistributed over all positions of the configuration (see Table 1). Figure 1 shows that the configurations were positioned on the screen so that the critical positions of the two lower figures occupied the same screen location, whereas there was no overlap of the two upper configurations.

Procedure

Participants were informed that either one or no target would be presented and they were required to decide as quickly as possible whether or not a target was present. A target was present in 67% of the trials. The frequencies of the unequally distributed target and the equally distributed target at the seven positions of the bird configuration within the target-present trials are shown in Table 1. In bird, position 3 (in a left to right order) and in wave, position 6 served as the critical position. The unequally distributed target of bird was the equally distributed target in wave and vice versa. For half of the participants the ╩ was the unequally distributed target in bird, for the other half it was the ╠. In each trial, one of the four figures of Figure 1 was selected with equal probability. All distractor characters were presented with equal probability in all possible positions of the bird and wave configuration, respectively. No information about the location distribution of the targets was given. The order of trials was random.

Each trial began with 4,400 Hz warning tone of 125 ms duration. The stimulus display was presented 600 ms after the offset of the tone and remained visible until response. Then speed and accuracy feedback was presented for 1 sec. The offset of the feedback was the onset of the warning tone for the next trial. The experiment was run in 4 blocks of 150 trials each (i.e., 4 × 100 presentations of each figure in Figure 1 containing a target, plus 4 × 50 presentations of each figure with no target present).

Results

Responses with RTs below 100 ms and above 3,000 ms were considered as outliers and discarded (2.13% of all responses, 4.56% of target absent trials, and 0.9% of target present trials).

Target Absent Trials

In the target absent trials the mean RT was 1,903 ms and the error rate was 5.89%. Since target absent trials were of no relevance to determine target localization, they were not analyzed further.

Table 3. Mean reaction times (in ms) and mean error rates (%) as a function of position and target type in Experiments 1–3.

	Position					
	Critical		Adjacent		Remote	
Experiment and target type	RT	ER	RT	ER	RT	ER
Experiment 1						
Equally distributed	1,235	7.56	1,308	13.37	1,296	15.18
Unequally distributed	1,119	5.46	1,313	11.59	1,365	21.32
Experiment 2						
Equally distributed	904	4.52	968	6.15	1,047	6.47
Unequally distributed	813	3.76	934	4.78	1,072	8.12
Experiment 3						
Equally distributed	634	5.03	770	9.98	1,003	7.05
Unequally distributed	646	4.49	814	7.81	1,058	11.98

Note. RT = reaction time; ER = error rate.

Target Present Trials

For each figure (bird-bottom, bird-top, wave-bottom, wave-top) and target type (unequally distributed vs. equally distributed), the mean RT from correct responses to targets at the critical position, the positions directly adjacent to the critical positions, and the remote positions were computed. The separation in adjacent and remote positions was made for the sake of comparability with previous reports. In a previous report, the separation in adjacent and remote locations was introduced to explore differences in response latencies despite formally identical target frequencies (see Table 1). This would indicate a carry-over of target expectancies from neighboring locations due to a limited spatial resolution of location-specific target expectancies analyses (see Hoffmann & Kunde, 1999, for a discussion of this issue). These mean RTs were entered into a three-way ANOVA for repeated measures with the variables position (critical, adjacent, and remote), target type (unequally distributed vs. equally distributed), and figure (bird-bottom, bird-top, wave-bottom, wave-top). The analysis led to a reliable effect of position, $F(2, 30) = 6.47$; $p < .01$; MSE = 13,7814.2. The position effect interacted with target type, $F(2, 30) = 14.60$; $p < .01$; MSE = 30,640.6, see Table 3. The unequally distributed target was detected faster than the equally distributed target in the critical position. The opposite pattern was present in the remote positions and an intermediate data pattern was observed at the positions adjacent to the critical positions.

Three additional effects reached significance. The main effect of figure, $F(3, 45) = 4.24$; $p < .05$; MSE = 41,008.7, the interaction of Figure × Position, $F(6, 90) = 17.60$; $p < .01$; MSE = 30,640.6, and the triple interaction of Figure × Target Type × Position, $F(6, 90) = 5.63$; $p < .01$; MSE = 20,547.0. All three effects were caused by rather high RTs for the equally distributed target in the adjacent positions of the bottom-wave figure. There is no obvious explanation for this untypical data pattern at hand. Since this influence was never found in previous experiments and also not in Experiments 2 and 3 of the present study that used the same figures, it will not be considered further.

The corresponding analysis of error rates mirrored the influence of position, $F(2, 30) = 21.27$; $p < .01$; MSE = 207.3, as well as the interactions of Position × Target Type, $F(2, 30) = 4.65$; $p < .02$; MSE = 149.9, and Figure × Position, $F(6, 90) = 2.30$; $p < .05$; MSE = 131.0.

Table 4. Mean reaction times (in ms) and mean error rates (%) as a function of overlap and target type at the critical positions in Experiments 1–3.

	Critical position			
	Nonoverlapping		Overlapping	
Experiment and target type	RT	ER	RT	ER
Experiment 1				
Equally distributed	1,248	6.31	1,223	8.82
Unequally distributed	1,137	5.39	1,101	5.53
Δ	*111*	*0.92*	*122*	*3.29*
Experiment 2				
Equally distributed	984	2.50	823	6.55
Unequally distributed	867	3.96	759	3.57
Δ	*117*	*−1.46*	*64*	*2.98*
Experiment 3				
Equally distributed	–	–	634	5.03
Unequally distributed	–	–	646	4.49
Δ	–	–	*−12*	*0.54*

Note. RT = reaction time; ER = error rate; Δ = difference between unequally distributed target and equally distributed target.

Comparison of Overlapping/Nonoverlapping Critical Positions

The above analysis did not consider whether the configurations overlapped on the screen or not. However, the detailed comparison of nonoverlapping vs. overlapping critical positions is crucial to judge which frame of reference has been applied (i.e., screen or configuration). Therefore, the data from the critical positions of the configurations were put into an additional analysis with the variables target type (unequally distributed versus equally distributed) and overlap (overlapping vs. nonoverlapping; see Table 4). This analysis led to a highly reliable influence of target type, $F(1, 15) = 23.28$; $p < .01$; MSE = 9,292.3). No other effect reached significance. In particular, the interaction of Target Type × Overlap was far from significant ($F < 1$). Single comparisons revealed significantly lower RTs for the unequally distributed targets than for the equally distributed targets at the nonoverlapping positions, $F(1, 15) = 9.43$; $p < .01$; MSE = 10,457.9, as well as at the overlapping positions, $F(1, 15) = 29.43$; $p < .01$; MSE = 4,015.06. No effects were significant in the same analysis of error data.

Discussion

Experiment 1 revealed two main results. First, it replicated the location-specific target probability effect in visual search. Apart from overall faster detection in the critical positions that contained targets most frequently, the unequally distributed targets were detected more quickly in the critical positions than the equally distributed targets, whereas the opposite pattern emerged at the remote positions. The adjacent positions revealed no systematic differences between target types (see Hoffmann & Kunde, 1999, for a discussion of the data pattern at adjacent positions).

Second, and more important in the present context, at the critical positions there was a highly reliable advantage of the configurations' unequally distributed targets independent of whether these positions overlapped on the screen or not, indicating a configuration-bound target localization. The result replicates a previous experiment (Kunde & Hoffmann, 1999: Exp. 3) with an identical distribution of targets but a different set of stimuli (geometrical line patterns instead of letters) and a different response mode (detection instead of discrimination). This reassures that the observed dominance of configurations over the screen is the result of the lower spatial uncertainty of targets in configural coordinates but not the result of specific letter identification mechanisms or response-related processes.

Experiment 2

Experiment 2 made one significant alteration. We reduced the screen-related variability of the targets by presenting the configurations unequally frequent at different positions on the screen. Still two distinct configurations were presented and the distribution of targets within the configurations remained unchanged. However, each of the two configurations now appeared five times more frequently in the lower than in the upper screen positions (see Figure 1). This left untouched the spatial uncertainty of targets in configuration-bound coordinates but reduced the uncertainty in screen-bound coordinates. According to our proposal this manipulation should increase the impact of a screen-related frame of reference on target localization. In terms of data, we expected that the advantage of the unequally distributed targets over the equally distributed targets would be reduced in the overlapping critical positions compared to the nonoverlapping positions.

When comparing the results of Experiment 1 to those of our previous study (Hoffmann & Kunde, 1999; Exp. 3), it is apparent that the response mode (detection or discrimination) as well as the stimulus material (line patterns or letters) are of little relevance for the selection of reference frames in visual search. Therefore, we adopted the discrimination response mode again (instead of the detection mode) in Experiment 2, which makes the interspersal of target absent trials superfluous and thus increases experimental efficiency. Also, we used letters again (instead of line patterns), which burden the attentional resources of our participants less than the very unfamiliar line pattern that we used in Experiment 1.

Method

Participants

Twenty undergraduates (4 men, 16 women) at the University of Würzburg, with normal or corrected to normal vision, aged from 19 to 35 years served as participants in fulfillment of a course requirement. Each participant was tested in a single session lasting about 45 min.

Apparatus, Stimuli, and Procedure

The same apparatus as in Experiment 1 was used. Instead of the geometrical line patterns of Experiment 1, letters served as stimuli. Targets were the letters F and H, and distractors were the letters B, D, G, K, P, T, and W (in Times font). Seven letters were again arranged to form the two configurations (bird and wave). Each distractor was again equiprobable at all positions of the bird and wave configuration. The frequencies of unequally distributed and equally distributed targets at the seven positions of each configuration were the same as in Experiment 1 (see Table 1). However, in contrast to Experiment 1, wave as well as bird were now presented five times as frequently in the lower than in the upper screen position. The unequally distributed target of bird was the equally distributed target in wave and vice versa. For half of the participants, the F was the unequally distributed target in bird; for the other half it was the H.

Participants were instructed that one target was always present, and that they were required to decide as quickly and as accurately as possible which of the two target letters was present. Half the participants pressed the left key when target F was detected and the right key when target H was detected. This mapping was reversed for the other half of participants. No information about the location distribution of the targets was given. The experiment was run in three blocks of 200 trials each, with a brief rest in-between.

Results

Responses with RTs below 100 and above 2,500 ms were considered outliers and discarded (1.03% of the data). RTs from correct responses were entered into an ANOVA for repeated measures with the variables position (critical, adjacent, and remote), target type (unequally distributed vs. equally distributed), and figure (bird-bottom, bird-top, wave-bottom, wave-top). This analysis led to significant effects of position, $F(2, 38) = 51.52$; $p < .01$; $MSE = 31{,}688.1$, and to a significant interaction of Position × Target Type, $F(2, 38) = 7.19$; $p < .01$; $MSE = 18{,}624.9$. At the critical positions, responses were faster for the unequally distributed target than for the equally distributed target, whereas the opposite was true at the adjacent and remote positions. However, the advantage for the unequally distributed target at the critical positions was stronger than the advantage of the equally distributed target at the remote positions resulting in a main effect of target type, $F(1, 19) = 12.85$; $p < .01$; $MSE = 10{,}225.8$. Additionally, RTs for targets in the two lower figures were faster than in the two upper figures, $F(3, 57) = 12.99$; $p < .01$; $MSE = 19{,}933.5$, for the effect of Figure, and the effect of position was also more pronounced in the two lower figures, $F(6, 114) = 3.42$; $p < .01$; $MSE = 23{,}440.7$ for the interaction of Figure × Position). The analysis of error data mirrored the influence of position from RTs analysis, $F(2, 38) = 5.04$; $p < .02$; $MSE = 85.8$. No other effect was significant.

Comparison of Overlapping/Nonoverlapping Critical Positions

A separate ANOVA for the critical positions with the variables target type (equally distributed vs. unequally distributed) and overlap (overlapping vs. nonoverlapping) revealed significantly faster responses for the unequally distributed targets over the equally distributed targets, $F(1, 19) = 27.26$; $p < .01$; $MSE = 6{,}056.7$). Responses were also significantly faster at the overlapping than at the nonoverlapping positions, $F(1, 19) = 50.93$; $p < .01$; $MSE = 7{,}166.8$. Additionally, the advantage of the unequally distributed target over the equally distributed target tended to be reduced at the overlapping positions, $F(1, 19) = 3.58$; $p < .08$; $MSE = 4{,}040.8$, for the interaction of Target Type × Overlap). Single contrasts revealed that the advantage of the unequally distributed target over the equally distributed target was significant at the nonoverlapping locations, $F(1, 19) = 18.06$; $p < .01$; $MSE = 7{,}680.0$, as well as at the overlapping locations, $F(1, 19) = 16.92$; $p < .01$; $MSE = 2{,}417.5$. No effects were significant in the analysis of error data.

Discussion

In Experiment 2 the uncertainty of targets in screen-related coordinates was reduced in comparison to Experiment 1, whereas the uncertainty of targets in configural positions was kept constant. This variation was expected to enhance the impact of a screen-related frame of reference. In agreement with this expectation, the data revealed effects of target frequencies at screen locations, which were absent in Experiment 1. First, the advantage for the configurations' unequally distributed targets was reduced at overlapping positions in comparison to nonoverlapping positions due to the fact that both targets appeared equally frequently at the overlapping screen location. The comparison of the data pattern between Experiments 1 and 2 shows a substantial reduction of the advantage of the unequally distributed targets at the overlapping positions (from 122 ms to 64 ms). One may take this as additional support for a stronger reliance on screen-bound target localization in Experiment 2 than in Experiment 1. However, due to the use of different stimulus material the RT-level was much higher in Experiment 1 and thus a between-experiments comparison should be viewed with caution. We therefore preferred to make our inferences on the within-experiment comparison of overlapping and nonoverlapping positions.

Second, responses in general were faster at overlapping than at nonoverlapping screen locations due to the fact that targets appeared altogether more frequently at the overlapping screen location.

Nevertheless target locations were still defined relative to the stimulus configurations bird and wave to a considerable degree. This is indicated by the still highly reliable advantage of the unequally distributed over the equally distributed targets at overlapping positions. This advantage requires a configuration-bound target localization. Thus, the results suggest that both types of reference frame were used concurrently – an issue we will consider in more detail in the General Discussion.

Experiment 3

In Experiment 3, the uncertainty of targets in screen-related locations was further reduced by presenting configurations exclusively at the lower two screen positions (see Figure 1). Again, this variation leaves the spatial uncertainty of targets in configurally defined positions intact, but reduces the uncertainty of targets in screen-defined locations. We therefore expected that targets would be located by relying more heavily (or even exclusively) on a screen-related frame of reference. If so, the RT advantage for the configurations' unequally distributed target over the equally distributed targets should be small (or even absent) at the only remaining overlapping location.

Method

Participants

Sixteen undergraduates (6 men, 10 women) at the University of Würzburg, with normal or corrected to normal vision, aged from 20 to 32 years served as participants in fulfillment of a course requirement. Each participant was tested in a single session lasting about 45 min.

Apparatus and Procedure

The apparatus, stimuli, and procedure were identical to Experiment 2, with the exception that the bird and wave configuration were now exclusively presented at the lower screen positions. The experiment was run in three blocks of 200 trials each.

Results

Responses with RTs below 100 ms and above 2,500 ms were considered as outliers and discarded (0.97% of all trials). RTs from correct responses were entered into an ANOVA for repeated measures with the variables position (critical, adjacent, and remote), target type (unequally distributed vs. equally distributed), and figure (bird, wave). The analysis revealed a reliable influence of position, $F(2, 30) = 224.23$; $p < .01$; $MSE = 11{,}052.2$, and target type, $F(1, 15) = 24.19$; $p < .01$; $MSE = 2{,}717.2$. No difference between targets was present at the critical positions ($F < 1$), but responses were faster for the equally distributed target than for the unequally distributed target at the remote positions, $F(1, 15) = 9.54$; $p < .01$; $MSE = 4{,}940.3$, as well as at the adjacent positions, $F(1, 15) = 8.09$; $p < .02$; $MSE = 3{,}762.9$.

In the error analysis the influence of position, $F(2, 30) = 18.46$; $p < .01$; $MSE = 19.6$, as well as the influence of target type, $F(1, 15) = 7.80$; $p < .02$; $MSE = 18.7$, were significant. Additionally, the interaction of Target Type × Position was reliable, $F(2, 30) = 4.73$; $p < .02$; $MSE = 27.5$. Single comparisons revealed a significantly higher error rate of the unequally distributed target than of the equally distributed target at the remote positions, $F(1, 15) = 15.30$; $p < .01$; $MSE = 25.5$, whereas no significant differences between targets were present at the adjacent and critical positions.

Discussion

Experiment 3 shows that with an appropriate adjustment of the screen-related target uncertainty, the indications of configural-related localization of targets are completely eliminated from the data pattern. At the overlapping location, the configurations' unequally distributed targets were detected as quickly as the respective equally distributed targets despite being presented here about five times more often, provided these locations were coded as positions in bird or wave. Note, that at the noncritical positions a significant advantage of the equally distributed targets over the unequally distributed targets was observed, corresponding to the fact that at these *screen* locations the equally distributed targets were presented more than three times more often than the respectively other target. Thus, there is no doubt that location-specific target frequencies were actually registered, but target frequencies referred exclusively to screen-related locations.

General Discussion

The present study investigated the selection of spatial frames of reference for the localization of targets in visual search. The results revealed that targets are less likely to be coded with respect to a certain spatial frame of reference the higher the spatial uncertainty of targets within this frame. The particular frames of reference in the present study were the configurations in which the targets were embedded and the screen on which the stimuli were presented. The reliance on these frames was pragmatically driven by the fact that the uncertainty of targets could easily be varied independently within these frames. Of course, our inferences are based on these particular frames of reference pitted against each other. We believe, however, that the present results are not confined to the particular experimental situation applied. Indeed we have found very similar results when different letter configurations (rather than letter configurations and the screen) serve as candidates for the coding of target locations (Kunde, 1999, Exp. 6).

Before considering the main theoretical implications of this result, two possible alternative accounts of the present data need to be discussed. First, an inspection of Table 4 shows that the decrease of RT differences between unequally and equally distributed targets at the overlapping critical location from Experiment 1 to 3 goes along with a decrease of the general RT level. Thus, the reduction of RT differences might result from a floor effect rather than indicating a change of the active reference frame. There are two arguments against this view. First, faster responding to a probable target than to an improbable target at a given location is likely to reflect benefits of the probable *and* costs of the improbable target (see Kingstone, 1992). A floor effect might disallow benefits but cannot prevent costs. Therefore, at least the elimination of detection benefits for the unequally distributed target in configural coordinates (Experiment 3) cannot result from a floor effect.

Second, in previous experiments with the same stimulus material and response mode, Hoffmann & Kunde (1999; Exp. 1 and 2) found substantial location-specific target differences with an RT level that was even below the one observed here, which strongly suggests that the size of location-specific target probability effects is independent of the overall RT-level. Moreover, in Experiments 1 and 2, the RT differences between the targets at the nonoverlapping locations was in the same range, although the overall RT level between experiments differed by about 300 ms (see Table 4).

The subjects were free to move their eyes in the present experiments. So a second alternative explanation might be that the results may have been affected by eye movements. First of all, it may well be that eye movements contributed to target-*unspecific* differences between different egocentric locations (e.g., the overall faster detection of targets appearing in the critical positions commonly containing a target; see Shaw & Shaw, 1977). However, our inferences are based on detection differences between different targets at a given location (i.e., differences between equally and unequally distributed targets in the critical and remote positions). As Miller (1988, p.464) already pointed out, it is hard to imagine how eye movements could contribute to such *identity-specific* differences that occur in a single egocentric location.

We now turn to the theoretical implications of the present results. It is well-grounded that stimuli are localized by the orienting of visual attention (Logan, 1994; Schneider, 1995; Treisman & Gelade, 1980; Treisman & Schmidt, 1982). Because there is little reason to doubt that target detection in the present experiments was attention-demanding, the present results contribute to the debate about the frames of reference visual attention relies on. Previous work primarily discussed whether attention relies on object-centered, scene-centered, or viewer-centered coordinates (Farah, Brunn, Wong, & Wallace, 1990; Gibson & Egeth, 1994; Robertson, 1995; Tipper, et al., 1999; Tipper & Behrmann, 1996; Umiltà et al., 1995). The flexible use of at least two frames of reference observed in the present study suggests that there is no unequivocal answer to this question. Rather than being restricted to one, and only one frame, visual attention seems to adapt flexibly to different frames of reference according to the spatial uncertainty of task-relevant stimuli within this frame.

This consideration may help to understand why in some studies certain frames of reference were more influential than other frames. To illustrate this issue, consider a study by Robertson (1995) that examined the frame of reference underlying the “rightward-advantage” in orienting visual attention (i.e., faster recognition of objects in the right than in the left hemispace). Participants judged the flexion of a letter (normal or mirror-image) in displays that were occasionally rotated by 90°, so that the display-based left and right locations corresponded to egocentric top and bottom locations. Performance was better in display-based right locations irrespective of rotation, suggesting an exclusive display-related basis of the rightward advantage. Consider, however, that due to rotation the entropy of the spatial distribution of the to-be-judged stimuli markedly differed between viewer-related (1.92 bit) and display-related coordinates (1.0 bit). Thus, the observed exclusive reliance on the display as the reference frame may simply reflect the much lower entropy of the distribution of the to-be-judged letters over the display-related locations. A straightforward prediction (perhaps worth testing) is that the reliance on a viewer-centered reference frame should increase the less frequently displays are rotated, i.e., the lower the entropy of the to-be-judged letters in viewer-centered coordinates.

Our results are consistent with observations from visual neglect patients. Behrmann & Tipper (1999) found that unilateral neglect (i.e., inattention to objects in one field) can refer to egocentric as well as object-based coordinates for a single patient at the same time. What is more, these authors showed that inattention to locations in terms of a certain frame of reference (e.g., object-based locations) increased the lower the spatial uncertainty of targets in that frame. Remarkably, our normal participants showed essentially the same behavior, though with an entirely different experimental task and a different measure of frame of reference reliance.

The adaptation of visual search to the reference frame, which is associated with the relatively lowest spatial uncertainty, implies that such uncertainties associated with all potential frames under consideration must have been temporarily available. Thus, before relying on a finally selected frame, target locations must have been coded with respect to more than one frame. There are at least two conceivable ways how such initial multiple coding and subsequent selection could be accomplished.

First, the visual system might encode several topographic relations of an attended stimulus in parallel (e.g., a stimulus of the present experiments might have been localized either as being in the center of the screen, in the middle of wave, left to the distractor "K" etc.). If an object is identified as a target, all (or at least several) concurrent spatial codes are associated with the target's identity, i.e., the target is tagged with multiple spatial codes. Tags that refer to a frame of reference with a low spatial uncertainty of targets will be reinforced more often and their strength will finally exceed that of all other tags. Second, it is also conceivable that targets are localized with respect to only one frame of reference at a time. A selection of the most advantageous frame then requires switching between different frames from time to time (or trial to trial), which, in the absence of any salient cues in the present experiments, will probably depend on participants' individual strategies and preferences.

The literature offers evidence consistent with both positions. On the one hand, data from sentence-picture matching and spatial compatibility tasks suggest that multiple locational codes of targets are activated automatically and in parallel (Carlson-Radvansky & Irwin, 1994; Carlson-Radvansky & Logan, 1997; Rosarwski & Proctor, 1996). On the other hand, it has been argued that the specification of spatial relations between objects can only proceed for one object and one referent at a time (Logan, 1994). The present study was not designed to decide between these alternatives and thus future research is warranted to clarify this issue.

To conclude, although the details of the underlying processes need to be further specified, the present study demonstrates the capability of the visual system to adapt to particular frames of reference that yield a low uncertainty (i.e., high predictability) in the spatial distribution of relevant objects. The uncertainty reduction hypothesis that motivated the investigation of this capability allows for simple and easily testable predictions that may apply to many other situations than visual search. We consider the further validation of this hypothesis a worthwhile future project.

Acknowledgement

We thank two anonymous reviewers for helpful comments on an earlier version of this paper.

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Received June 24, 2004
Revision received August 18, 2004
Accepted August 23, 2004

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