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Sources of position-perception error for small isolated targets

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Abstract It has often been reported that, in the presence of static reference stimuli, briefly presented visual targets are perceived as being closer to the fixation point than they actually are. The first purpose of the present study was to investigate whether the same phenomenon can be demonstrated in a situation without static reference stimuli. Experiment 1, with position naming as the task, showed that such a central shift is also observed under these conditions. This finding is of importance because it completes an explanation for central near-location errors in the partial-report bar-probe task. The second purpose of the present study was to provide an explanation for these central shifts. For this explanation information about the exact size of the central shift is required. In Exps. 2, 3, and 4, with cursor setting as the task, it was attempted to assess more precisely the size of the central shifts. These experiments revealed that two different factors determine the results in cursor setting tasks; a factor "target position" and a factor "cursor position." Experiment 5 showed that it is the point of fixation, not the fixation point, that serves, at least in part, as the reference point in this type of task. All the findings together allow us to conclude that the target positions are underestimated by about 10%. From vision research it is known that saccadic eye movements, performed for bringing a target in the fovea, also show an undershoot of about 10%. It is therefore concluded that the system in charge of saccadic eye movements also provides the metric in visual space within a single eye fixation.

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General introduction

This study is concerned with a peculiar phenomenon in the visual perception of spatial position: the tendency to perceive a briefly presented small stimulus as closer to the point of fixation than it actually is. This study has its origin in a problem of explanation, encountered with the partial-report bar-probe task (see Hagenaar & van der Heijden, 1997; see also below). In the course of our investigations, however, it appeared that the results obtained might have important consequences for theories of space perception and selective attention.

The partial-report bar-probe task, introduced by Averbach and Coriell (1961), is a classic tool for studying visual information processing and selective attention. In the most-often used version of the task, a horizontal row of letters is briefly exposed – for example, for 50 ms. The subjects have to name one letter of the row. That letter is indicated through a visual cue, for example, a briefly exposed small barmarker in close spatial contiguity with the letter. The cue is presented before, during, or at various intervals after the exposure of the letter display.

This bar-probe task has produced a consistent pattern of results. Two main findings have often been reported. Firstly, accuracy of report depends upon moment of presentation of the cue. If the cue just precedes the letter or is shown simultaneously, accuracy is quite high (approximately 75% correct). The same result is found when the cue immediately follows the letter display. Accuracy decreases, however, when the cue is further delayed. At a delay of about 250 ms, accuracy reaches an asymptotic level of about 35% correct. Secondly, accuracy of report depends upon the position of the letter to be named. Accuracy of report is higher for the letters in the center and at the ends of the row than for letters in between, that is, the correct reports are distributed in the shape of a "W" across positions (see, e.g., Averbach & Coriell, 1961; Mewhort, Campbell, Marchetti, & Campbell, 1981; Hagenaar & van der Heijden, 1995, 1997).

With regard to the interpretation of the results obtained with this task, three successive steps can be distinguished (see Hagenaar & van der Heijden, 1997). Initially, following Averbach and Coriell (1961), only the percentages of correct reports as a function of spatial position and of moment of appearance of the cue were regarded as pertinent. These percentages of correct reports were taken as unbiased estimates of the subject's ability to identify the indicated letters. Therefore, initially, it was simply taken for granted that each error reflected a failure of perceptual analysis or of identification (see, e.g., Estes, 1978).

Later, following Townsend (1973), a detailed analysis of the errors was used. In this analysis, the erroneous responses are classified as either item errors or location errors, with an item error referring to the report of a letter that was not in the array, and a location error referring to the report of a letter that was in the array but not in the position indicated. It appeared that the great majority of errors were location errors and that most location errors were near-location errors, that is, they consisted of the name of a letter adjacent to the letter indicated (see, e.g., Mewhort et al., 1981; Hagenzieker, van der Heijden & Hagenaar, 1990; Hagenaar & van der Heijden, 1995, 1997). This outcome strongly suggested that it was not so much problems of perceptual analysis or identification, but problems of localization that imposed the major limitations on performance in partial-report bar-probe tasks (see, e.g., Campbell & Mewhort, 1980; Mewhort, 1987; Mewhort et al., 1981).

Recently, the near-location errors were further analyzed. Hagenaar and van der Heijden (1997) distinguished between central near-location errors and peripheral near-location errors, with a central near-location error referring to the report of an adjacent letter on the foveal side of the indicated letter, and a peripheral near-location error referring to the report of an adjacent letter on the peripheral side of the indicated letter. From this analysis it appeared that the great majority of near-location errors were central near-location errors; a preponderance of response letters came from a position adjacent to, and on the foveal side of, the target. This outcome not only supported the view introduced by Mewhort and associates that localization problems are the major source of errors in partial-report bar-probe tasks, but also suggested a detailed explanation of the location errors in terms of erroneous spatial perception of the briefly presented cue, that is, the bar.

The explanation forwarded by Hagenaar and van der Heijden (1997) was based on an observation reported by Rauk and Luuk (1980). These authors investigated the accuracy of the absolute judgements of the spatial position of briefly presented (0.5 ms) isolated dots that could be regarded as members of a horizontal (or vertical) one-dimensional array. They observed that subjects made many errors in naming the position of such a dot. In particular, they observed that "…in most cases the means of the erroneous responses were shifted towards the central fixation point…" From this observation they concluded "…a general tendency to estimate the position of an object as if it was more centrally located than it actually was" (Rauk & Luuk, 1980, p.150). Rauk and Luuk were by no means the only investigators that observed these systematic position errors. Similar or closely related observations, for example, were reported by Bedell and Flom (1981); Leibowitz, Myers and Grant (1955); Mateeff and Gourevich (1983, 1984); Mateeff and Hohnsbein (1988); Mitrani and Dimitrov (1982); Osaka (1977); O'Regan (1984); Rose and Halpern (1992); and Skavenski (1990).

Hagenaar and van der Heijden (1997) explained their main result – a preponderance of central near-location errors – by assuming that the letters in the row were perceived in the correct positions, but that the short-duration barmarkers that they used to indicate the position of the target were perceived like the dots in Rauk and Luuk's (1980) experiments, that is, as being shifted towards the central fixation point. The additional assumption that, with simultaneous presentation of array and cue, the letter array helps in correctly fixing the position of the barmarker and that this help is increasingly lacking with an increasing temporal separation between array and cue, allowed them an explanation of why (central near) location errors increased with increasing cue delays.

In this way, it seemed as if a phenomenon often reported by basic vision research achieved an adequate explanatory status for a group of results obtained in an important, classical, visual information processing and selective attention task. Nevertheless, two important issues required further investigation.

Firstly, closer inspection of the vision research literature showed that the evidence supporting Hagenaar and van der Heijden's (1997) explanation is not overwhelming. As stated, Hagenaar and van der Heijden invoked the assumption that the array can be of help in correctly fixing the position of the cue. In other words, they assumed that apparent central displacements of the cue will especially be observed in the *absence* of reference points in the visual field as in the bar-probe task with a delayed (or advance) cue. However, in the vision research literature, precisely these central displacements in the absence of reference points have apparently never been reported. In a review, Rose and Halpern (1992, p. 290) conclude, "What is common to all experiments is the use of static reference stimuli and brief or transiently presented target stimuli." Thus, the stimulation situation used in vision research is different in an essential aspect from the situation in bar-probe tasks with a delayed (or advance) cue. Whether under the latter conditions, that is, in the absence of static reference points, central displacements will also be observed has still to be assessed. The demonstration of central displacements in the absence of static reference points was the first goal of our investigations.

Secondly, even when central displacements of a briefly presented target in the absence of static reference points can be demonstrated, the explanation of central near-location errors in partial-report bar-probe tasks, forwarded by Hagenaar and van der Heijden (1997), remains incomplete. Then one phenomenon – the central near-location errors – is explained in terms of another phenomenon – the central displacements of the cue – but the explanation of the latter phenomenon is still completely missing. Therefore, in the course of our research, the search for the *cause* of the central displacements of briefly presented targets became the second goal of our investigations.

Experiment 1

Introduction

In our first experiment we investigated whether, in the absence of static reference points, central displacements of a briefly presented line can be demonstrated. The exposure conditions used were similar to those in a partial-report bar-probe task with a delayed (or advance) cue. On each trial, subjects saw a briefly presented small vertical line – a bar – that was positioned below an imaginary horizontal array with seven equi-spaced positions. The array was centered at the fixation point. The spatial dimensions of the displays were chosen in such a way that they were close to the spatial dimensions of the displays used in the partial-report bar-probe tasks reported by Hagenaar and van der Heijden (1995, 1997). The subjects had to indicate the perceived position of the bar by naming one of the seven positions.

Method

Subjects. Eight students at the University of Leiden served as paid subjects. All of them had normal or corrected-to-normal vision. The subjects were tested individually.

Apparatus. The experiment was run using a standard, high-resolution, low-radiation SVGA computer display. Screen size was reduced to a rectangle of about 8.5 by 4.8 deg of visual angle by means of a window cut in a sheet of black paper. The screen was housed in a low-illuminated room. The presentation of the trial events and the recording of the responses were controlled by a standard 486/33-Hz PC.

The subject was seated at a table in front of the screen at a viewing distance of about 95 cm. The subject's head was supported and fixed by a chin-rest. The subject initiated stimulus exposure by pressing a button placed on the table in front of him/her.

Stimulus material. Each display contained an (imaginary) horizontal array of seven equi-spaced positions centered at the central fixation point. The total length of the (imaginary) array was 3.10 deg and the height was .36 deg of visual angle. The inter-position spaces were about .49 deg of visual angle. In the first 21 practice trials the positions in the array were labelled by means of digits. The digits ran from "3," "2," and "1" on the left through "0" in the center to "1," "2," and "3" on the right. This array was not shown in the rest of the practice trials and in the experimental trials.

At each trial a vertical target line was shown below one of the seven positions in the (imaginary) array. The length of a target line was about .35 deg and the width was about .03 deg of visual angle. The line was presented below the (imaginary) array, with its top at a distance of about .60 deg of visual angle from the array.

Before stimulus exposure a (dim) fixation cross was displayed at the center. The width of the fixation cross was .12 deg and the height was .12 deg of visual angle.

Design. In the main experiment each subject saw a unique series of 350 trials, being 50 replications of the seven line positions. The 350 trials were ordered randomly for each subject.

Procedure. Each subject took part in one individual session. The session started with a 5-min period to adapt to the illumination level in the room. In this period and prior to the first stimulus presentation, the subject was informed about the task and about the positions and verbal labels that were used, that is, from "3 on the left" through "0" to "3 on the right."

The subjects were instructed to look at the (dim) fixation cross and to initiate stimulus presentation when the cross was sharply in focus. On stimulus initiation the fixation cross disappeared. After 100 ms the line was shown at one of the seven target positions. After that, the line disappeared. The subject was requested to name the position of the line and to guess if unsure.

Each subject received 84 practice trials. In the first 21 practice trials the array of digits was shown. In these practice trials the exposure time of the line was 400 ms. In the later 63 practice trials the array of digits was not shown, and the exposure time of the line was successively lowered from 400 ms to 30 ms. Then the subject undertook the 350 experimental trials. The exposure time of the line was 30 ms. A short rest period was given when asked for by the subject. Feedback was given on the first 21 practice trials only, that is, when the array of digits was shown.

Results

For analyzing the data, the positions were recoded as "−3," "−2," and "−1" (on the left) through "0" (at the center) to "+1," "+2," and "+3" (on the right). Table 1 gives, averaged across subjects, the proportions of reported positions of the line, $R(TP)$, for each of the seven target positions, TP.

A perceived target position, $p(TP)$, was defined as the weighted mean of the reported positions. Per subject and per position, the deviation of the perceived target

Table 1 The proportions of reported positions, $R(TP)$, for each of the seven target positions, TP

TP	R(TP)						
	−3	−2	−1	0	+1	+2	+3
−3	0.513	0.458	0.030				
−2	0.028	0.673	0.284	0.017			
−1		0.053	0.813	0.135			
0			0.047	0.878	0.075		
+1				0.175	0.788	0.038	
+2				0.008	0.384	0.590	0.020
+3					0.038	0.565	0.398

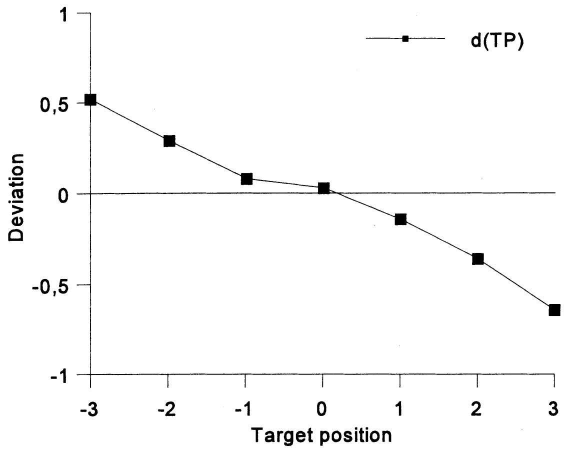

Fig. 1 The deviation of the perceived position from the target position, $d(TP)$, as a function of the target position

position from the actual target position, $d(TP)$, was calculated. Figure 1 presents these deviations, averaged across subjects, for each of the seven target positions, TP.

Deviation

To investigate the effect of target position on the deviation of the perceived position from the actual target position, two analyses of variance were conducted. The first analysis included all the target positions from −3 to +3. The second analysis included the target positions from −2 to +2. Both ANOVAs yielded a highly significant effect of target position: $F\,(6{,}42) = 30.59$, $p < .01$ for positions −3 to +3, and $F\,(4{,}28) = 32.33$, $p < .01$ for positions −2 to +2.

Perceived position[1]

To examine the metric underlying the perceived positions, two linear regression analyses relating deviations of perceived position from target position to actual target positions were performed. The regression equation used was:

$$d(TP) = B \times TP + A \qquad (1)$$

where B is the regression coefficient on actual target position and A is a constant describing the intercept of the function. In the first regression analysis all the positions were included, that is, the positions from −3 to 3. In the second analysis the outside positions were excluded.

[1] In all regression equations reported in this study the deviations per subject, $d(TP)$, per position, TP, were used as data, i.e., there were n(subjects) × p(positions) pairs of numbers per equation. As a result, the R**2s measure the explained between-subjects and between-positions variances. Therefore, with large between-subjects differences (Exps. 2, 3, and 4) the R**2s will be relatively small.

The first regression analysis, including the outer positions −3 to 3, yielded the function:

$$d(TP) = -.18 \times TP - .03(R^2 = .85,\ SE = .15)\ . \qquad (2)$$

Further analysis showed that the intercept constant of −.03 ($SE = .02$) was not different from zero, $t(55) = -1.52$, $p > .10$. The regression coefficient of −.18 ($SE = .01$) was different from zero, $t(55) = -17.56$, $p < .01$. The regression coefficient shows that the subjects underestimated the target position by about 18%.

The second regression analysis, excluding the outer positions −3 to 3, yielded the function:

$$d(TP) = -.15 \times TP - .02(R^2 = .76,\ SE = .12)\ . \qquad (3)$$

Further analysis showed that the intercept constant of −.02 ($SE = .02$) was not different from zero, $t(39) = -.97$, $p > .10$. The regression coefficient of −.15 ($SE = .01$) was different from zero, $t(39) = -11.06$, $p < .01$. The regression coefficient shows that the subjects underestimated the target position by about 15%.

Discussion

The results obtained strongly suggest that, also in the absence of static reference points as in the bar-probe task with delayed (or advance) cues, subjects tend to perceive the positions of briefly presented targets closer to the fixation point than they actually are. This is already apparent from Table 1, which shows that errors in reporting the target position are more likely to be inwards than outwards, that is, more likely to be closer to than further away from the fixation point. The analyses of variance over the signed, that is, positive and negative, deviations and the linear regression analyses relating deviations of perceived target position from actual target position to the actual target positions support this observation. In addition, these analyses show that the magnitude of the central displacement increases with increasing target eccentricity.

In the present experiment no outward errors were possible on positions +3 and −3; the response "4" was not allowed. Therefore, it can be argued that, because of this truncation, the results are artificially biased in the direction of the fixation point. The data are not in accord with this view, however. From Table 1 it is easy to derive that for the set of positions (−2, −1, +1, +2) – that is, for the positions on which inward and outward errors were possible – about 88% of the error responses came from inward positions, and about 12% from outward positions. Also, the analysis of variance over the deviations and the regression analysis relating deviations of perceived position from target position to actual target positions with the outer positions, −3 and +3, deleted, shows that this truncation cannot explain our results; the results for the restricted set of target positions and for the full range of target positions are nearly the same.

Experiment 2

Introduction

From out Exp. 1 and from the vision research literature, it follows that the central displacement of a briefly presented target is an easily observable phenomenon. An important remaining question, of course, is what is at the basis of these central displacements. As will become clear in the General discussion, to answer this question, information about the exact magnitude of the central displacements of the targets is essential. For two reasons, however, the regression coefficient(s) obtained in Exp. 1 can only be regarded as approximate indications of the central displacements. Firstly, subjects had to indicate the position of the target by employing one verbal label from the set of verbal labels assigned to the seven different target positions. It cannot be excluded that this "discrete" mode of responding often forced subjects into indicating the perceived position in a coarse and approximate way. Secondly, no outward errors were possible on positions −3 and +3. While this "truncation" cannot be regarded as the cause of the central displacements (see the data for positions −2 and +2 in Fig. 1; see also the regression coefficients in Exp. 1), it hampers the assessment of the exact magnitude of the central displacements.

To evade these problems and to arrive at a better estimate of the exact magnitude of the displacements, in our second experiment the same brief target exposure conditions as in Exp. 1 were used, but instead of a verbal response, a "visual" response was required; the subjects had to move a continuously visible "cursor" from the fixation point to the perceived position of the target. Two cursor step-size conditions were used: a large step-size condition in which the cursor moved from position to position to obtain results comparable with the results of Exp. 1, and a small step-size condition in which the cursor moved in five steps from position to position to avoid the coarse and approximate responding problem. To evade the "truncation" problem, in both conditions positions beyond −3 and +3 could also be indicated.

Method

Subjects. Eight students at the University of Leiden served as paid subjects. All of them had normal or corrected-to-normal vision. None of them had participated in the previous experiment. The subjects were tested individually.

Apparatus. Except for the following modifications the same apparatus as in Exp. 1 was used. In this experiment, the subject viewed the screen through a circular tube, in order to avoid distraction by irrelevant events. The subject initiated stimulus exposure by pressing the spacebar on a keyboard placed in front of him/her. The subject also used this keyboard for indicating the position of the target (see below).

Stimulus material. The same stimuli as in Exp. 1 were used.

Response. The subject had to indicate the perceived position of the target by means of a cursor, a very small dot. The cursor dot appeared in the center position (position 0). The subject moved the cursor dot to the right or the left by pushing the left or the right cursor key on the keyboard. The range of cursor positions was not limited to the seven target positions on the (imaginary) array but extended to the left and right border of the screen.

Design. There were two cursor movement conditions: A large step (LS) condition and a small step (SS) condition. In the LS condition each key-press moved the cursor from one position to the next position. In the SS condition each key-press moved the cursor 1/5 of the inter-position distance.

In the main experiment each subject received two blocks of trials. In one block, the cursor dot moved with large steps (LS condition), and in the other block the cursor dot moved with small steps (SS condition). The order of the blocks was balanced over subjects. Each block consisted of 140 trials, being 20 replications of the seven target positions. Thus, for each subject, the total main experiment consisted of 2 (LS condition and SS condition) × 7 (target positions) × 20 (replications) = 280 trials.

Procedure. Each subject took part in one individual session. The session started with a 5-min period to adapt to the illumination level in the room. In this period the subject was informed about the task, the blocks, the seven positions, and the cursor adjustment.

The subjects were instructed to look at the fixation cross and to initiate stimulus presentation when the cross was sharply in focus. Upon stimulus initiation, the fixation cross disappeared. After 100 ms the target line appeared for 30 ms at one of the seven target positions. Then the target line disappeared. The cursor dot appeared 250 ms after the disappearance of the target. The subject could then move the cursor dot to the position where he/she had seen the target. The subject was instructed to press the spacebar when the perceived position of the cursor dot was as close as possible to the perceived position of the target. After pressing the spacebar, the cursor dot disappeared, the fixation cross reappeared, and the subject could start the next trial.

Each experimental block was preceded by five practice blocks of 14 trials each. The practice blocks differed in the exposure time of the target. Over the five blocks, this time was successively lowered from 1 s to 30 ms, that is, to the exposure time used in the main experiment. The first practice block differed from the other four in two respects. Firstly, the target exposure was accompanied by a display showing all the positions numbered from 3 via 0 to 3 (see also Exp. 1). Secondly, to provide feedback about the correctness of the response, the target line reappeared at the correct position after the response.

Results

"Position" and "perceived target position" were defined as in Exp. 1. Figure 2 presents, for each of the seven target positions, *TP*, averaged across subjects, the deviation of the perceived target position from the actual target position, $d(TP)$, for the two cursor movement conditions, large steps (*LS*) and small steps (*SS*).

Deviation

To investigate the effect of type of cursor movement, LS and SS, and target position on the deviations of the

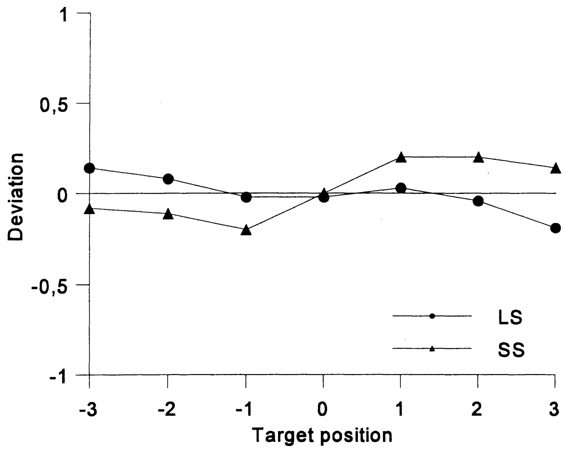

Fig. 2 The deviation of the perceived position from the target position as a function of the target position, for each of the two cursor conditions (*LS* and *SS*). See text for further details

perceived target positions from the actual target positions an analysis of variance was performed. Neither the main effect of cursor movement ($F(1,7) = 2.06$, $p >$ .10) nor the main effect of target position ($F(6,42) = 0.55$, $p > .10$) were significant. The interaction between type of cursor movement and target position was, however, highly significant ($F(6,42) = 9.64$, $p < .01$).

Perceived position[2]

To examine the metric underlying the perceived positions, a linear regression analysis, relating deviations of perceived position from target position to actual target positions, was performed for each of the two cursor movement conditions (see also Exp. 1).

For the LS condition, the regression analysis yielded the function:

$$d(TP) = -.04 \times TP - .00(R^2 = .14,\ SE = .21)\ . \qquad (4)$$

Further analysis showed that the intercept constant of −.00 ($SE = .03$) was not different from zero, $t(55) = -.13$, $p > .10$. The regression coefficient of −.04 ($SE = .01$) was different from zero, $t(55) = -2.99$, $p > .01$. The regression coefficient shows that the subjects underestimated the target position by about 4%.

For the SS condition, the regression analysis yielded the function:

$$d(TP) = .06 \times TP + .02(R^2 = .11,\ SE = .34)\ . \qquad (5)$$

Further analysis showed that the intercept constant .02 ($SE = .05$) was not different from zero, $t(55) = .51$, $p > .10$. The regression coefficient of .06 ($SE = .02$) was different from zero, $t(55) = 2.63$, $p < .05$. The regression coefficient shows that the subjects overestimated the target position by about 6%.

[2] See Footnote 1.

Discussion

In Exp. 1, with verbal responses, the results clearly indicated central displacements of the target. In the present experiment, with size of cursor movement as the response, virtually no evidence for such displacements is obtained. The analysis of variance over the deviations revealed no more than a significant interaction between type of cursor movement and target positions. This outcome strongly suggests that, on the average, with size of cursor movement as the dependent variable, the positions are correctly perceived and indicated, albeit that type of cursor movement has a small but systematic effect on the correctness of the responses.

Recent related results reported by Bridgeman, Peery, and Anand (1997) strongly suggest that nothing is wrong with our data; these investigators also consistently found central displacements with position naming (as in our Exp. 1) but not with manual pointing at the position (as in the present experiment). However, there is a reason to assume that something is wrong with the conclusion that, with size of cursor movement as the dependent variable, the positions are correctly perceived and indicated.

As stated in the Introduction, it is reasonable to assume that in the present experiment the small step (SS) condition gives a more adequate indication of the perceived target positions than the large step (LS) condition. With the small, 0.2, steps subjects can simply much better approximate the perceived target positions than with the large, 1.0, steps. Thus, at this point in our line of experimentation, the estimates obtained in the SS condition are the data that have to be taken seriously and explained. The results and analyses indicate that in this SS condition the subjects tend to position the cursor more *peripherally* than the target was (see Fig. 2 and the linear regression equation with the positive regression coefficient of .06). However, Exp. 1 provides no reason whatsoever to assume that subjects perceive the target more peripherally than it actually was. Thus, when we take the outcome of the present experiment seriously and when we also accept the outcome of Exp. 1, then the combination of results strongly suggests that an *extra factor* is introduced with the continuously visible cursor as the measuring stick for perceived target position. This extra factor certainly requires further investigation and elaboration.

Experiment 3

Introduction

The two foregoing experiments together strongly suggest that in an experiment in which a movable cursor is used to indicate the position of a briefly presented target, two factors determine the data:

1. The first factor is the perceived position of the target, or, for short, the "target position"; subjects tend

to estimate the position of a target more centrally than it actually is (see Exp. 1).

2. The second factor is the perceived (end) position of the cursor, or, for short, the "cursor position"; subjects tend to place the cursor at the peripheral side of the perceived target position (compare the results of Exps. 1 & 2) and sometimes even more peripherally than the target actually was (see the SS condition Exp. 2).

In Exp. 2, these two factors, "target position" and "cursor position," were completely confounded or correlated, in the sense that both factors always had the same – positive or negative – direction. A target presented and perceived at the right required a cursor movement to the right (positions +1, +2, and +3); a target presented and perceived in the center required no cursor movement (position 0), and a target presented and perceived at the left required a cursor movement to the left (positions −1, −2, and −3). The data collected in Exp. 2 can therefore be considered as being determined by an underlying factor "target position" that is modulated or transformed by a correlated factor "cursor position." Because of this correlation or confounding, it is impossible to disentangle the contributions of the two factors and to estimate their respective effects.

The purpose of our third experiment was to disentangle the contributions of the factors "target position" and "cursor position" in the small step, SS, condition (see Exp. 4 for the large step, LS, condition). To this end, besides a "cursor starts in the middle" (M) condition, also the conditions "cursor starts at the left" (L) and "cursor starts at the right" (R) were used. In the L condition for all (perceived) target positions, a (positive) cursor movement to the right is required, and in the R condition for all (perceived) target positions, a (negative) cursor movement to the left is required. In this way, in the L and R conditions the factor "cursor position" is un-correlated or additive with the factor "target position," and their separate contributions can be assessed[3].

Method

Subjects. Nine students at the University of Leiden served as paid subjects. All of them had normal or corrected-to-normal vision. None of the subjects had participated in the previous experiments. The subjects were tested individually.

Apparatus, stimulus material and procedure. These were the same as in Exp. 2.

Response. The cursor could start at three positions: in the middle (M), at the left (L), and at the right (R) of the (imaginary) array. In condition M, the cursor started from the center position (position 0) and had to be moved to the left or to the right. In condition L, the cursor started from a point three positions to the left of position −3, that is, at position −6, and had to be moved to the right. In condition R, the cursor started from a point three positions to the right of position +3, that is, at position +6, and had to be moved to the left. In all three conditions the cursor moved in small steps, that is, 0.2 positions per key push.

Design. The main experiment consisted of three blocks that differed in the starting position of the cursor. Each block consisted of 140 trials, being 20 replications of the seven target positions. Thus, per subject, the main experiment consisted of 3 (cursor positions) × 7 (target positions) × 20 replications = 420 trials. Over subjects the order of blocks was varied by using a Latin square.

Results

"Position" and "perceived target position" were defined as in the previous experiments. Figure 3 gives, for each of the seven target positions, *TP*, averaged across subjects, the deviation from the actual target position, *d*(*TP*), for the three cursor starting positions (*Left*, *Middle*, and *Right*).

Deviation

To investigate the effect of the starting position of the cursor and the target position on the deviations of the perceived positions from the actual target positions, two analyses of variance were conducted. The first analysis included all three starting conditions of the cursor dot, while the second analysis included only the left and right starting conditions.

In the first analysis, the main effect of starting position, L, M, and R, was highly significant, $F(2,16) = 17.28$, $p < .01$. The main effect of target position was not significant, $F(6,48) = 1.92$, $p > .10$. The interaction between starting position and target position was highly significant, $F(12,96) = 10.68$, $p < .01$.

In the second ANOVA, the main effect of starting position, L and R, was highly significant, $F(1,8) = 17.61$, $p < .01$. The main effect of target position was also highly significant, $F(6,48) = 9.01$, $p < .01$. The interac-

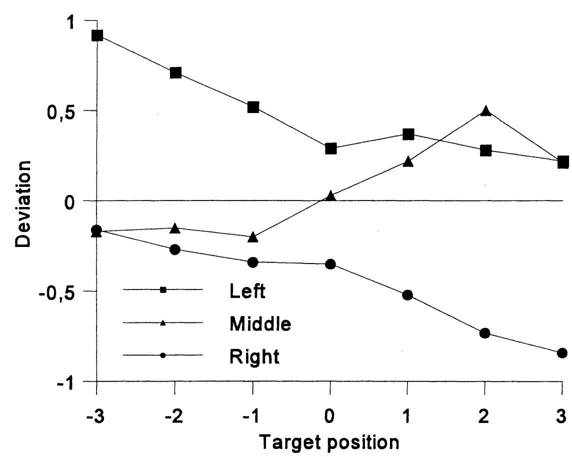

Fig. 3 The deviation of the perceived position from the target position as a function of the target position, for each of the three cursor starting positions (*Left*, *Middle*, and *Right*). See text for further details

[3] The factor "cursor position", for instance, is additive with the factor "target position" when the cursor is always moved a distance, *d*, too far. For relatively large distances, as used in the present experiment and in Exp. 4, this seems a reasonable assumption (see also the General discussion).

tion between starting position and target position was not significant, $F(6,48) = 1.63$, $p > .10$.

Perceived position[4]

To examine the metric underlying the perceived positions, a linear regression analysis, relating deviations of perceived position from target position to actual target positions, was performed for each of the three starting conditions (see also Exp. 1).

For condition M, the regression analysis yielded the function:

$$d(TP) = .08 \times TP + .00(R^2 = .18,\ SE = .35)\ . \qquad (6)$$

Further analysis showed that the intercept constant of .00 ($SE = .04$) was not different from zero, $t(62) = .00$, $p > .10$. The regression coefficient of .08 ($SE = .02$) was different from zero, $t(62) = 3.70$, $p < .01$. The regression coefficient shows that the subjects overestimated the target position by about 8%.

For condition L, the regression analysis yielded the function:

$$d(TP) = -.12 \times TP + .48(R^2 = .27,\ SE = .38)\ . \qquad (7)$$

Further analysis showed that the intercept constant of .48 ($SE = .05$) was different from zero, $t(62) = 9.89$, $p < .01$. The regression coefficient of −.12 ($SE = .02$) was different from zero, $t(62) = -4.75$, $p < .01$. This regression coefficient suggests that the subjects underestimated the target position by about 12%.

For condition R, the regression analysis yielded the function:

$$d(TP) = -.11 \times TP - .45(R^2 = .16,\ SE = .51)\ . \qquad (8)$$

Further analysis showed that the intercept constant of −.45 ($SE = .06$) was different from zero, $t(62) = -7.03$, $p < .01$. The regression coefficient of −.11 ($SE = .03$) was different from zero, $t(62) = -3.46$, $p < .01$. This regression coefficient suggests that the subjects underestimated the target position by about 11%.

Discussion

The analyses of variance and the linear regression equations show that condition M differs in important ways from conditions L and R. The analyses of variance indicate this by yielding a significant interaction between starting positions and target positions when condition M is included, but not when analysis is restricted to conditions L and R. The linear regression equations indicate this by yielding virtually identical values for the regression coefficients and virtually identical (absolute) values for the intercepts in the L and R condition, but strongly deviating values in condition M.

A comparison of the linear regression equations for the small step (SS) condition of Exp. 2, and the M condition of the present experiment shows that the estimated parameters are nearly the same (regression coefficients: .06 and .08; intercepts: .02 and .00). Thus, the M condition of the present experiment is simply what it has to be: a successful replication of the identical SS condition in Exp. 2.

A comparison of the linear regression equations for the L condition and the R condition in the present experiment shows that the values of the estimated parameters are virtually the same (regression coefficients: −.12 and −.11; absolute intercepts: .48 and .45). The only difference between the two regression equations is that the intercept is positive in the L condition (subjects place the cursor a constant distance too far to the right) and that the intercept is negative in the R condition (subjects place the cursor a constant distance too far to the left).

A comparison of the parameters for the L condition and the R condition with the parameters for the M condition (and the SS condition of Exp. 2) reveals that with a peripheral starting point the regression coefficients are much smaller (−.12 and −.11 vs. .08 and .06), and the absolute intercepts are much larger (.48 and .45 vs. .00 and .02). This difference in parameters already suggests that in the L and R condition we were successful in disentangling the contributions of the factors "target position" and "cursor position." Whereas in the M condition (and in Exp. 2), both factors contribute to the regression coefficient and none to the intercept, in the L and R condition the effect of "target position" seems to show up as a moderate shrink, that is, as an "undershoot," in the regression coefficients, and the effect of "cursor position" is restricted to the intercepts and shows up as a displaced measuring stick, that is, as a constant "overshoot" (when the cursor starts at the left, the stick moves to the right, and when the cursor starts at the right, the stick moves to the left). The fact that the regression coefficients for the L and R conditions (−.12 and −.11) are rather close to the regression coefficients obtained in Exp. 1 (−.18 and −.15) with verbal responses further supports this interpretation (see also Exp. 4 and the General discussion).

Experiment 4

Introduction

The results presented up to now suggest that, in our cursor setting experiments, two factors determine the cursor settings; the factor "target position" and the factor "cursor position." Moreover, the results of Exp. 3 suggest that with peripheral starting points, in the function relating the deviations of the perceived target positions from the actual target positions to the actual

[4] See Footnote 1.

target positions, the factor "target position" shows up in the regression coefficient, and the factor "cursor position" in the intercept. The present experiment serves to substantiate this interpretation further. The experiment has its starting point in a finding in our Exp. 2.

In Exp. 2, two cursor movement conditions were used, a small step (SS) condition and a large step (LS) condition. The analysis of variance revealed a significant interaction between type of cursor movement, LS and SS, and target position. The linear regression analysis yielded different *regression coefficients* for the two movement conditions: −0.4 for the LS condition and .06 for the SS condition. In the two conditions in Exp. 2, the target presentations were exactly the same. Thus, it is highly unlikely that the factor "target position" was responsible for the difference in results. The only difference between the two conditions was in the type of movement of the cursor: small (0.2) steps and large (1.0) steps. Thus, it must have been the factor "cursor position" that caused the difference in regression coefficients.

From our analysis, presented in the first paragraph of this introduction, an interesting prediction follows. That prediction is that, if with peripheral cursor starting positions in the functions relating deviations to target positions, a difference between the LS condition and the SS condition shows up, that difference should *not* appear in the *regression coefficients* (determined by the factor "target position"), as was the case in Exp. 2, but in the *intercepts* (determined by the factor "cursor position"). The present experiment, in combination with Exp. 3, tests this prediction. The experiment is a replication of Exp. 3, with large steps instead of small steps.

Method

Subjects. Nine students at the University of Leiden served as paid subjects. All of them had normal or corrected-to-normal vision. None of them had participated in the previous experiments. The subjects were tested individually.

Apparatus, stimulus material, design and procedure. These were the same as in Exp. 3.

Response. The same three starting conditions as in Exp. 3 were used. In all three conditions the cursor moved in large (1.0) steps over the (imaginary) array.

Results

"Position" and "perceived target position" were defined as before. Figure 4 presents for each of the seven target positions (*TP*), averaged across subjects, the deviation from the actual target position, *d*(*TP*), for the three cursor starting positions (*Left*, *Middle*, and *Right*).

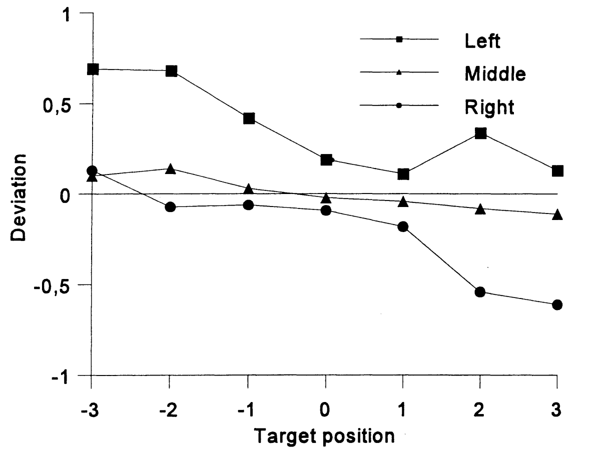

Fig. 4 The deviation of the perceived position from the target position as a function of the target position, for each of the three cursor starting positions (*Left*, *Middle*, and *Right*). See text for further details

Deviation

To investigate the effect of the starting position of the cursor and the target position on the deviation of the perceived positions from the actual target positions, two analyses of variance were conducted. The first analysis included all three starting conditions of the cursor dot, whereas the second analysis included only the left and the right starting conditions.

In the first analysis, the main effect of starting position, L, M, and R, was highly significant, $F(2,16) = 10.51$, $p < .01$. The main effect of target position was also significant, $F(6,48) = 6.56$, $p < .01$, as was the interaction between starting position and target position, $F(12,96) = 2.68$, $p < .01$.

In the second analysis, the main effect of starting position, L and R, was highly significant, $F(1,8 = 11.49$, $p < .01$. The main effect of target position was also significant, $F(6,48) = 8.59$, $p < .01$, as was the interaction between starting position and target position, $F(6,48) = 3.71$, $p < .01$.

Perceived position[5]

To investigate the metric underlying the perceived positions, a linear regression analysis, relating deviations of perceived position from target position to actual target positions, was performed for each of the three starting conditions (see Exp. 1).

For condition M, the regression analysis yielded the function:

$$d(TP) = -.04 \times TP + .00(R^2 = .07,\ SE = .30)\ . \qquad (8)$$

Further analysis showed that the intercept constant of .00 ($SE = .04$) was not different from zero, $t(62) = .08$,

[5] See Footnote 1.

$p > .10$. The regression coefficient of −.04 ($SE = .02$) was different from zero, $t(62) = -2.16$, $p < .05$. The regression coefficient shows that the subjects underestimated the target position by about 4%.

For condition L, the regression analysis yielded the function:

$$d(TP) = -.10 \times TP + .40(R^2 = .15,\ SE = .50)\ . \qquad (9)$$

Further analysis showed that the intercept constant of .40 ($SE = .06$) was different from zero, $t(62) = 6.36$, $p < .01$. The regression coefficient of −.10 ($SE = .03$) was different from zero, $t(62) = -3.33$, $p < .01$. This regression coefficient suggests that subjects underestimated the target position by about 10%.

For condition R, the regression analysis yielded the function:

$$d(TP) = -.12 \times TP - .20(R^2 = .34,\ SE = .33)\ . \qquad (10)$$

Further analysis showed that the intercept constant of −.20 ($SE = .04$) was different from zero, $t(62) = -4.94$, $p < .01$. The regression coefficient of −.12 ($SE = .02$) was different from zero, $t(62) = -5.63$, $p < .01$. This regression coefficient suggests that the subjects underestimated the target position by about 12%.

Discussion

While not apparent in the analyses of variance, the linear regression equations show that condition M differs in important ways from conditions L and R. The linear regression equations indicate this by yielding similar values for the regression coefficients and similar (absolute) values for the intercepts in the L and R conditions, but deviating values in condition M.

A comparison of the linear regression equations for the large step (LS) condition of Exp. 2 and the M condition of the present experiment shows that the estimated parameters are nearly the same (regression coefficients: −.04 and −.04; intercepts: −.00 and .00). Thus, the M condition of the present experiment is simply what it has to be: a successful replication of the identical LS condition in Exp. 2. As in Exp. 2, in the M conditions of Exp. 3, and of the present experiment, the effect of step size is reflected in the regression coefficients (SS: +.08; LS: −.04), and not in the intercepts (SS: .00; LS: .00).

A comparison of the linear regression equations for the L condition and the R condition in the present experiment shows that the values of the parameters are of the same order of magnitude (regression coefficients: −.10 and −.12; absolute intercepts: .40 and .20). The main difference between the two regression equations is that the intercept is positive in the L condition (subjects place the cursor too far to the right), and that the intercept is negative in the R condition (subjects place the cursor too far to the left).

A comparison of the parameters for the L condition and the R condition with the parameters for the M condition (and the LS condition of Exp. 2) reveals that with a peripheral starting point, the regression coefficients are smaller (−.10. and −.12. vs. −.04 and −.04) and the intercepts are larger (absolute values of .40 and .20 vs. .00 and .00). This again suggests that in the L and R condition we were successful in disentangling the contributions of the factors "target position" and "cursor position" (see the Discussion of Exp. 3). The fact that the regression coefficients for the L and R conditions are rather close to the regression coefficients obtained in Exp. 1 with verbal responses (−.18 and −.15) further supports this interpretation (see also the General discussion).

With central cursor starting points an effect of step size – large steps versus small steps – shows up in the regression coefficients (see above). The prime purpose of the present experiment was to test the prediction, following from our analysis, that with peripheral starting positions any effect of step size should not show up in the regression coefficients (determined by the factor "target position"), but in the intercepts (determined by the factor "cursor position"). The data are in accord with this prediction. With peripheral – L and R – starting positions, the regression coefficients in the present experiment with the large steps and in the previous experiment with the small steps are nearly exactly the same (−.10 and −.12 vs. −.12 and −.11), while the absolute values of the intecepts are indeed somewhat smaller (.40 and .20 vs. .48 and .45). We shall return in the General discussion to what, in our view, causes this difference between step-size conditions.

Experiment 5

Introduction

Experiments 2, 3, and 4, with cursor setting responses, strongly suggest that two factors determined the results: the factor "target position" and the factor "cursor position." Moreover, the results obtained in the L and R conditions of Exps. 3 and 4, especially when taken in combination, strongly suggest that for peripheral starting points, in the function relating the perceived target position to the actual target position, the factor "target position" shows up as an undershoot in the regression coefficients, and the factor "cursor position" as a constant overshoot in the intercepts. This outcome forces us to provide at least the beginning of an answer to the question: What is hidden behind the factor "target position" and the factor "cursor position"?

To find the beginning of an answer to this question it is important to note that, in our experiments, there is an essential difference between the conditions under which the target is perceived and the conditions under which the cursor is perceived. The target is presented briefly while subjects are looking at the fixation point. Under these conditions no useful eye movements are possible (see, e.g., Rayner, Slowiaczek, Clifton, & Bertera, 1983;

see also van der Heijden, 1992, Chap. 2). Thus, during target perception the subjects' point-of-fixation coincides with the fixation point. The cursor, however, is presented during a considerable period of time. It is therefore highly likely that subjects move their eyes and fixate the cursor, at least temporarily. Thus, during cursor perception the subjects' point-of-fixation does not necessarily coincide with the fixation point.

This difference in viewing conditions for the target and the cursor makes the question of which reference point subjects use for assessing a position (or a distance) – the fixation point or the point-of-fixation – of vital importance. When the subjects always use the (position of the) fixation point as the reference point, no difference between the factors "target position" and "cursor position" is to be expected. For both the target and the cursor there is one and the same, stable, reference point. However, when the (position of the) point-of-fixation serves as the reference point, differences between the factors "target position" and "cursor position" cannot be excluded. The (position of the) fixation point then serves as the reference point for the target while another, unknown and possibly cursor-induced (position of the) point-of-fixation can serve as the reference point for the cursor.

In our last experiment we attempted to assess what reference point the subjects use, the (position of the) fixation point or the (position of the) point-of-fixation. The experiment is a modified version of Exp. 1 with verbal responses. Just before target presentation the subjects had to make a saccadic eye movement from the left or from the right to a briefly presented central fixation point. From vision research it is known that a saccadic eye movement is nearly always too short (see, e.g., Deubel, 1991; see also the General discussion). Thus, with this interpolated saccade, the (position of the) point-of-fixation does not coincide with the (position of the) central fixation point. Under these experimental conditions the subjects' verbal responses can reveal what reference point is used. When the (position of the) central fixation point serves as the reference point, approximately the same results as in Exp. 1 are to be expected. However, when the (position of the) point-of-fixation serves as the reference point, systematic deviations will be observed: with saccades from the left the eye will land at the left of the central fixation point and all targets will be seen and reported as somewhat shifted to the right, and with saccades from the right the eye will land at the right of the central fixation point and all targets will be seen and reported as somewhat shifted to the left.

Method

Subjects. Eight students at the University of Leiden served as paid subjects. All of them had normal or corrected-to-normal vision. None of them had participated in the previous experiments. The subjects were tested individually.

Apparatus. The experiment was run on the same apparatus and under the same conditions as in Exp. 1, except for screen size. In this experiment the screen size was approximately 16 by 12 deg of visual angle.

Stimulus material. The stimulus was made up of two sequential components. In the first component a fixation cross was shown at the left or right of the center at an eccentricity of about 5.1 deg of visual angle. The width and height of the fixation cross was .12 deg of visual angle. This fixation cross was replaced by a small letter in a circle. The letter shown was an "H," an "S," a "T," or a "Z." The circle had a diameter of about .30 deg of visual angle. The second component was exactly the same as the stimulus used in Exp. 1. The "fixation cross" of this stimulus was displayed at the center of the screen. The width and height of the central cross was .12 deg of visual angle.

Design. Each subject saw a unique series of 280 trials, being 20 replications of the factorial combination of two initial fixation positions (left and right) and seven line positions. The 280 trials were ordered randomly for each subject.

Procedure. Each subject served in one individual session. The session started with a 5-min adaption period in which the subject was informed about the task, the positions, and verbal labels that were used, that is, from "3 on the left" through "0" to "3 on the right." The subjects were instructed to look at the (dim) fixation cross on the left or on the right of the screen and to initiate stimulus presentation when that cross was sharply in focus. On stimulus initiation the fixation cross disappeared and the letter in the circle appeared. After 100 ms the letter and circle disappeared. Then, after 10 ms, the central cross appeared. The subjects were asked to try to look at the central cross. The target line appeared 100 ms after the disappearance of the central cross. Then the line disappeared. The subject was requested to report the letter first, then to indicate the position of the line with respect to the central cross, and to guess if unsure. Each subject received 92 practice trials. Feedback was only given on the first 28 practice trials, that is, only on the first 28 practice trials was the array of digits ('3210123') shown. During practice, the exposure time of the central cross and of the line was successively lowered from 400 ms to the exposure times used in the experiment, that is, to 90 ms for the central cross and to 30 ms for the line. Then the subject received the 280 experimental trials. Table 2 presents the sequence of events and the exposure times in the experimental trials.

Results

Subjects named the letter correctly in 94% of the trials. Only the trials in which the subjects reported the letter correctly were used in the subsequent analyses. For the other trials it is not known whether the subject looked at the first fixation cross. A perceived position, $p(TP)$, was

Table 2 The sequence of events and the exposure times in the experimental trials in Exp. 5

Event	Exposure time
Peripheral cross	Till stimulus initiation
Letter in circle	100 ms
Blank screen	10 ms
Central cross	90 ms
Blank screen	100 ms
Target	30 ms

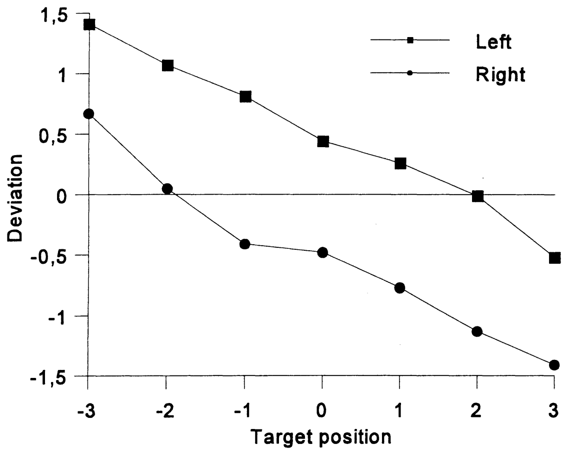

Fig. 5 The deviation of the perceived position from the target position as a function of the target position, for each of the two initial fixation positions (*Left* and *Right*). See text for further details

defined as in Exp. 1. Figure 5 presents for each of the seven target positions (*TP*), averaged across subjects, the deviations of each perceived position from the actual target position, *d*(*TP*), for the two fixation conditions (*Left* and *Right*).

Deviation

To investigate the effect of target position on the deviations of the perceived positions from the actual target positions, two analyses of variance were conducted. The first analysis included all target positions from −3 to +3. The second analysis included the target positions from −2 to +2. Both analyses showed a highly significant main effect of fixation side, $F(1,7) = 39.51$, $p < .01$ for positions −3 to +3, and $F(1,7) = 40.40$, $p < .01$ for positions −2 to +2. The main effect of target position was also highly significant, $F(6,42) = 25.79$, $p < .01$ for positions −3 to +3, and $F(4,28) = 13.58$, $p < .01$ for positions −2 to +2. The interaction between fixation position and target position was not significant in either analysis, $F(6,42) = 1.68$, NS, for positions −3 to +3, and $F(4,28) = .87$, NS, for positions −2 to +2.

Perceived position

To examine the metric underlying the perceived positions, two linear regression analyses relating deviations of perceived position from target position to actual target position were performed for each of the two fixation sides. In the first regression analysis all the positions were included, that is, the positions from −3 to +3. In the second analysis the outside positions were excluded.

For the left fixation side, the first regression analysis, including the outer positions −3 to +3, yielded the function:

$$d(TP) = -.31 \times TP + .48(R^2 = .68, SE = .44)\ . \qquad (11)$$

Further analysis showed that the intercept constant of .48 ($SE = .06$) was different from zero, $t(55) = 8.05$, $p < .01$. The regression coefficient of −.31 ($SE = .03$) was different from zero, $t(55) = -10.65$, $p < .01$. The second regression analysis, excluding positions −3 to +3, yielded the function:

$$d(TP) = -.29 \times TP + .50(R^2 = .70, SE = .42)\ . \qquad (12)$$

Further analysis showed that the intercept constant of .50 ($SE = .07$) was different from zero, $t(39) = 7.62$, $p < .01$. The regression coefficient of −.29 ($SE = .05$) was different from zero, $t(39) = -6.16$, $p < .01$.

For the right fixation side, the first regression analysis, including the outer positions −3 to +3, yielded the function:

$$d(TP) = -.33 \times TP - .52(R^2 = .52, SE = .63)\ . \qquad (13)$$

Further analysis showed that the intercept constant of −.52 ($SE = .08$) was different from zero, $t(55) = -6.13$, $p < .01$. The regression coefficient of −.33 ($SE = .04$) was different from zero, $t(55) = -7.70$, $p < .01$. The second regression analysis, excluding positions −3 to +3, yielded the function:

$$d(TP) = -.28 \times TP - .57(R^2 = .30, SE = .63)\ . \qquad (14)$$

Further analysis showed that the intercept constant of −.57 ($SE = .10$) was different from zero, $t(39) = -5.79$, $p < .01$. The regression coefficient of −.28 ($SE = .07$) was different from zero, $t(39) = -4.01$, $p < .01$.

Discussion

Saccadic eye movements have a latency of at least 150 ms (see, e.g., Rayner et al., 1983). In the present experiment the saccadic eye movement could only be initiated after enough letter information was acquired and the central fixation cross had appeared. The sequence of events and exposure durations used in the present experiment (see table 2) were such that, with these constraints, upon arrival of the eye on the second point-of-fixation the central fixation cross had already disappeared. Thus, for the present experiment it is reasonable to assume that the (position of the) second point-of-fixation was not on the (position of the) central fixation cross but more to the left with initial fixation at the left, and more to the right with initial fixation at the right (see, e.g. Deubel, 1991; see also the Introduction).

As stated in the Introduction, when the (position of the) central fixation cross always serves as the reference point for estimating position (or distance), no differences between initial fixation at the left and initial fixation at the right are to be expected. With both initial fixation points the same reference point for assessing target position (or distance) is used. However, when the (position of the) point-of-fixation serves as the reference point, systematic differences between the two initial fixation points have to be expected: deviations to the right with initial fixation at the left, and deviations to left with initial fixation at the right (see the Introduction).

The results of the present experiment are clearly in accord with the assumption that the (position of the) point-of-fixation serves, at least in part, as the reference point for assessing target position (or distance). The regression equations show that with initial fixation at the left, all target positions are reported to be slightly shifted to the right (intercept values of .48 and .50), and that with initial fixation at the right, all target positions are reported to be slightly shifted to the left (intercept values of −.52 and −.57).

As stated in the Introduction, Exps. 2, 3, and 4 strongly suggest that two factors determined the results: the factor ‘‘target position’’ and the factor ‘‘cursor position.’’ For the factor ‘‘target position’’ the (position of the) fixation point and the (position of the) point-of-fixation coincide, whereas for the factor ‘‘cursor position,’’ this is not necessarily the case. Therefore, the main outcome of the present experiment that the point-of-fixation serves, at least in part, as a reference point can serve as a starting point for answering the question what is hidden behind these two factors. In the General discussion we return to this starting point.

General Discussion

Our study had its origin in a problem of explanation encountered with the partial-report bar-probe task. In this task a row of letters is briefly presented and subjects have to name the letter that is indicated by a briefly presented visual cue, for example, by a small vertical line or bar under the letter. Especially when there is a temporal separation between letter row and visual cue, subjects make many errors. Most of these errors are central near-location errors, that is, most of the errors involve the name of a letter from a position adjacent to, and on the foveal side of, the target (see our General introduction).

Hagenaar and van der Heijden (1997) explained these central near-location errors in terms of misperception of the position of the visual cue. They assumed that the letters in the row were perceived in the correct position, but that, especially with a temporal separation between letter row and visual cue, the briefly presented cue was perceived as being shifted towards the central fixation point. Unfortunately, firm supporting evidence for this hypothesis was missing. While vision research had produced abundant evidence for this kind of misperception in the presence of static reference stimuli, the evidence in situations without static reference points as in the bar-probe task was lacking.

One of the purposes of the experiments reported in this study was to provide this missing evidence. In all our experiments a vertical target line was presented in an empty visual field 100 ms after disappearance of a central fixation cross. This type of target presentation adequately mimics the exposure situation of the cue in a partial-report bar-probe task with a temporal separation between letter row and visual indicator. The outcome of the experiments clearly supports Hagenaar and van der Heijden’s (1997) conjecture. In Exp. 1, and also in the L(eft) and R(ight) conditions of Exps. 3 and 4, a clear and significant apparent shift of the briefly presented lines in the expected direction, that is, a ‘‘perceptual undershoot,’’ was observed. Thus, the results obtained complete Hagenaar and van der Heijden’s explanation of an intriguing phenomenon observed in a classic visual information processing and selective attention task. The centrally displaced delayed bar captures attention (see Jonides & Yantis, 1988; Yantis & Jonides, 1984; see also van der Heijden, 1992), and often a central near-location error will be made.

Of course, an adequate explanation for a phenomenon observed in the partial-report bar-probe task is something, but an adequate explanation of the apparent central shifts of a briefly presented small target in the absence of static reference points, that is, of the ‘‘perceptual undershoot,’’ is something completely different. Therefore, the second purpose of our investigations was to find the beginning of an explanation of the central shifts. In our view, with the data we gathered and presented, a tentative but reasonable explanation can now indeed be offered. To show this, we shall first return to the results of Exp. 5, then we shall look again at the results of Exps. 2, 3, and 4 – the experiments with the moving cursor – and finally we shall turn to the explanation of the central shifts.

From the results of Exp. 5 we concluded that the point-of-fixation, and not the fixation point, served as the reference point in the visual assessment of position (or distance). With regard to this conclusion, two problematic issues that can be raised are not important, in the present context. The first issue concerns the question whether the point-of-fixation serves as the only reference point. Given the data presented, it cannot be excluded that there are further, additional, landmarks, for example, the border of the screen, that serve the same function. The second issue concerns the exact interpretation of the parameters, the regression coefficient and the intercept, of the linear functions for Exp. 5. Given the complexity of the task that had to be performed it cannot be excluded that different types of trials, for example, trials with eye movements and trials without eye movements, contributed to these parameters. These issues are not important, however, because for our explanation, we only need the major reliable result: The point-of-fixation serves, at least in part, as a reference point.

For understanding the results of Exps. 2, 3, and 4, in which a moving cursor was used to indicate the perceived position of the target, it is worthwhile to distinguish two parts in each experimental trial, a ‘‘target perception part’’ and a ‘‘cursor perception part.’’ In the target perception part, the subjects assessed the position (or distance) of the target. That target appeared for 30 ms, 100 ms after the disappearance of the fixation point. These presentation conditions effectively excluded directed eye movements during this part of a trial. In the cursor perception part, subjects tried to reproduce the assessed position (or distance) with the cursor. They could take all the time they needed to move the cursor to the wanted position. Thus, in this part of the trial, there can have been a number of eye movements and eye fixations. From the eye movement literature it is known that it is difficult not to follow a stepwise moving target with saccadic eye movements (see, e.g., Findlay, 1987). Exactly this eye movement behaviour can help us to understand the results obtained in Exps. 2, 3, and 4[6].

In Exp. 2 (and in the M conditions of Exps. 3 and 4) the target was presented while subjects fixated the central fixation point. The subjects assessed the distance between this fixation point (= point-of-fixation) and the target. The cursor also appeared at the fixation point (= point-of-fixation). While the subjects tried to reproduce the assessed distance with the cursor, the cursor moved in the direction of the (perceived position of the) target, and the subjects' eyes moved, at least some distance, with the cursor. When this shift is incompletely corrected, the point-of-fixation no longer corresponds with the position of the fixation point: it is shifted away from that position in the direction of the (perceived position of the) target. From Exp. 5 we know that the point-of-fixation serves, at least in part, as the reference point. Thus, in the cursor perception part, the reference point is displaced in the direction of the (perceived position of the) target. The assessed distance is reproduced with this shifted reference point. As a result, as measured from the fixation point, the cursor will be moved too far; there will be a "movement overshoot."

This "shifted reference point" hypothesis, in combination with the "perceptual undershoot," immediately explains the results obtained in the conditions with the cursor starting point in the middle. In these conditions the movement overshoot of the cursor cancels and therefore masks the perceptual undershoot. The difference between the results obtained in the Small Step condition of Exp. 2 and in the M condition in Exp. 3 (regression coefficients of .06 and .08, i.e., "overshoot") an the results obtained in the Large Step condition of Exp. 2 and in the M condition of Exp. 4 (regression coefficients of −.04 and −.04, i.e., "undershoot") is understandable with the additional assumption that it is easier to prevent following the cursor, or easier to correct the shift, when the cursor moves in (slow, clearly visible) large steps than in (fast, less visible) small steps.

In the L and R conditions of Exps. 3 and 4, the target perception part of the trial was exactly the same as in the conditions just discussed. The cursor perception part, however, was different. The cursor appeared three positions to the left of −3 in the L conditions, and three positions to the right of +3 in the R conditions. The results obtained in these conditions can be explained in exactly the same way as the results obtained in the M conditions, when one additional assumption is introduced. That additional assumption is that with all larger cursor travel distances, for example, with three positions or more, the size of the cursor-induced shift of the point-of-fixation is about the same. This seems a reasonable assumption because other visual cues, such as the border of the screen, are present to prevent too great deviations. In the L and R conditions of Exps. 3 and 4, the distance to be moved was always at least three positions. Thus, when all other conditions are equal, about the same shift of the point-of-fixation has to be excepted with all target distances. In the L conditions the cursor moved to the right, and consequently the point-of-fixation shifted to the right. In the R conditions the cursor moved to the left, and consequently the point-of-fixation shifted to the left. In both cases and for all target positions, the reference point was displaced a constant small distance in the direction in which the cursor moved.

The data of the L and R conditions of Exps. 3 and 4 are completely in accord with this "shifted reference point" analysis, given the "perceptual undershoot." There is no effect of starting point of cursor in the regression coefficients (−.12 and −.10 for starting point left, and −.11 and −.12 for starting point right) and a large effect in the intercepts (+.48 and +.40 for starting point left, and −.45 and −.20 for starting point right). This pattern of results indicates a similar shift in the direction in which the cursor moved for all target positions. (The difference between the intercepts in the Large Step and Small Step conditions can be explained in the same way as the corresponding difference between the regression coefficients in Exp. 2 and between the M conditions of Exps. 3 and 4; see the discussion of the M conditions.)

The last phenomenon that still remains to be explained is the central shift, that is, the "perceptual undershoot"; Exp. 1 and the L and R conditions in Exps. 3 and 4 all indicated that, also in the absence of static reference stimuli, a briefly-presented target line is reported as being closer to the (objective or subjective) fixation point than that it actually was. As already stated and as will appear further on, for the explanation of this central shift a *quantitative* estimate of the size of the shift is of fundamental importance. From the foregoing it will be clear that, in our view, the regression coefficients of the linear functions for the L and R conditions in Exps. 3 and 4 provide the best quantitative estimates of the size of this apparent inward movement. In these conditions, inward and outward errors were possible for all positions (there was

[6] When we planned and performed the cursor experiments, we were not aware that eye movements could be involved. After the experiments were run, we investigated with a dual Purkinje eye tracker whether eye movements occurred in a situation identical to the one in Exp. 2. All subjects followed the moving cursor with their eyes.

no "truncation problem," as in Exp. 1, where the range of responses was restricted). In addition, whereas Exps. 2, 3, and 4 forced us to distinguish two factors that contribute to the cursor settings, the data were completely in accordance with the view that, in the linear regression equations for the L and R conditions, the regression coefficients reflected the factor "target position." The regression coefficients for the L and R conditions in Exps. 3 and 4 equalled −.12, −11, −.10 and −.12. We therefore have to conclude that the subjects underestimated the target positions or target distances by around 10%.

In the introduction to Exp. 5, we already mentioned that vision research has shown that a saccadic eye movement, performed for bringing a target in the fovea, is nearly always too short (see also, e.g., Becker, 1972; Bedell & Flom, 1983; Bracewell, Husain, & Stein, 1990). Vision research also provides *quantitative* information about the size of this undershoot. The information of fundamental importance is that these saccadic eye movements are also about 10% too short. For instance, Deubel (1991) showed that the saccadic eye movement covers approximately 90% of the distance between the initial fixation point and the position of the target, and that the remaining distance is reduced by a post-saccadic drift (PSD).

It will be clear that the outcome of our experiments (about 10% "perceptual undershoot") and the information from eye movement research (about 10% "saccadic undershoot") forces us to assume that the central shift, that is, the "perceptual undershoot," has to be explained in terms of properties and function of the saccadic eye movement system. It leaves us with no other viable possibility than to subscribe to the space perception theories that postulate that the system in charge of the guidance of saccadic eye movements is also the system that provides the metric in perceived visual space within a single eye fixation (see Lotze, in Boring, 1957, for an early example; see also, e.g., Koenderink, 1990; Wolff, 1987). In fact, the results of our experiments and analyses provide this group of theories with important new supporting empirical evidence.

Of course, further selective attention research, involving eye movement registration and position judgements, is certainly needed for the further unraveling of the intricate relation between the phenomena observed in the partial-report bar-probe task (central near-location errors: Hagenaar and van der Heijden, 1997), the perception-of-position tasks (central displacements: the present study), and the saccadic eye movement tasks (central undershoots: Deubel, 1991). Also, as the present study has made abundantly clear, in that further research one has to be very careful with the interpretation of the data obtained in position judgement experiments with cursor (or arrow) setting as the task, because a shift of reference point is easily induced (see, e.g., Adam, Paas, Ekering, & Van Loon, 1995; Adam, Ketelaars, Kingma, & Hoek, 1993; Honda, 1985; O'Regan, 1984; Wong & Mack, 1981).

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