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Comparison of three psychophysical methods for measuring displacement in frontal plane motion

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Displacement is a phenomenon related to representations of dynamic stimuli. The final position of a target moving in the frontal plane is not remembered correctly, but is instead shifted in the direction of the motion. Previous studies of displacement have mostly used the constant-stimuli method and the adjustment method. Although both methods usually yielded forward displacements, the task of responding activates different processes in the two methods, which could result in different outcomes. The purpose of the present study was to examine whether the magnitude of displacement is affected by the measurement method. Three psychophysical methods were used: the constant-stimuli method, the staircase method, and the adjustment method. Direction and acceleration of the motion were also varied. The results showed that displacement is affected by motion acceleration (being the smallest for decelerated motion) and by motion direction (displacement was larger for motion to the right than for motion to the left). The constant-stimuli method and the staircase method gave comparable results, whereas the displacement obtained with the adjustment method was larger. Also, the variability of data differed between the methods, being the largest for the adjustment method. The results indicated that when experimenting with displacement a special consideration should be given to the selection of the psychophysical method, where as adjustment method should be used with caution.

Key words: displacement, psychophysics, method of constant stimuli, staircase method, adjustment method

When a target moving in the frontal plane suddenly disappears and observers are asked to localize the final position reached by the target, the remembered position is usually displaced from the actual position in the direction of target motion. This is called representational momentum or *displacement*[1]. Freyd and Finke (1984) argued that the phenomenon represents a mental analogue of the physical momentum of a moving real-world object. An object that acquires momentum cannot stop instantly, but is instead still moving forward for some time. Analogically, the representation of a moving target is supposed to have the same inertial properties, so when the target vanishes, the memory of its final position is displaced forward.

Various hypotheses address the grounds of this phenomenon (for a review see Hubbard, 2005). First studies (e.g. Finke & Freyd, 1985; Freyd, 1987; see also Shepard, 1984) claimed that displacement reflects an adaptive internalization of physical principles in environmental change. In accordance with this explanation, it was found in many studies that displacement depends on motion properties, such as target velocity (Finke, Freyd, & Shyi, 1986; Freyd & Finke, 1985; Hubbard & Bharucha, 1988), acceleration (Finke et al., 1986; Poljanšek, 2002), and other (for a review see Hubbard, 2005). Several studies (e.g., Hubbard, 1994; Hubbard & Bharucha, 1988; Verfaillie & d'Ydewalle, 1991) revealed that displacement was also affected by various factors that were not related to physical principles (e.g., target identity, surrounding context, and observer's expectations about future motion direction) and concluded that displacement may be a consequence of informed anticipation. On the other hand, displacement may be the outcome of certain low-level

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[1] The effect has been given various names which all more or less directly reflect the underlying hypothesis/explanation of the illusion. In the context of the memory-related accounts it is called either the representational momentum (e.g. Freyd and Finke, 1984) or memory displacement (e.g. Hubbard and Bharucha, 1988), whereas in the context of the perceptual account, it is often merely described in terms of its behavioural manifestation - i.e. mislocalisation/displacement of the final position of a moving target (e.g. Kerzel, 2000).

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processes, such as extrapolation of the position of moving objects performed automatically by our visual system (Nijhawan, 1994) or our motor system (Kerzel, 2003b) in order to compensate for neural delays that would interfere with goal directed movements (e.g. catching). The phenomenon reflects the mechanisms that bridge the gap between perception and action, which is why investigating displacement is highly relevant to vision science and psychophysics (Hubbard, 2006).

Studies on displacement used different psychophysical methods to assess the magnitude of displacement. Most of the studies used probe judgment, which is psychophysically reduced to the method of constant stimuli (Hubbard, 2005). In probe judgment, a stationary probe (of the same shape as the target) appears after the target has vanished and observers compare the position of the probe with the remembered final position of the target. They usually judge whether these positions are same or different, but they may also judge whether the probe was presented at the final position of the target or was it shifted forward or backward relative to the actual vanishing point of the target. The position of the probe relative to the final position of the target is varied across trials, and the proportions of different types of judgments are measured. Usually the percentage of the 'same' responses is calculated and the psychometric curve is drawn. The peak of the curve or the average of the 'same' responses distribution determines the magnitude of the displacement. With the three-response alternative of the method, the .50 proportion of responses *forward* and *backward* can indicate the 'forward' and the 'backward' threshold (analogous to the lower and the upper threshold) and the mean between the two thresholds can indicate the magnitude of the displacement (analogous to the point of subjective equality in the standard version of the constant-stimuli method; see Guilford, 1954).

Another method of measuring displacement is the cursor-positioning method, which is psychophysically reduced to the method of adjustment (Hubbard, 2005). Different versions of the method may be used. In the first version, no probe appears on the display. Instead, observers have to touch the remembered final position of the target on the screen (see Kerzel, 2003b) or to position the cursor of the computer mouse to the (subjective) vanishing point of the target and to confirm their judgment by pressing a mouse button (see Hubbard & Bharucha, 1988; Kerzel, 2003b). In the second version of the adjustment method, the probe (with the same characteristics as the target, i.e. same shape, color, and size) appears at a random position close to the actual vanishing point of the target, and observers have to use direction keys on the keyboard to adjust its position and then press the Enter key to confirm their adjustments (see Poljanšek, 2002).

Compared to the processes involved in the probe judgment, the processes involved in the cursor-positioning may be much more complex. Whereas the probe judgment involves only recognition, the cursor-positioning requires recall and additional psychological processes, such as motor functions and dividing attention between the maintenance of the representation of the target's final position and concurrent processing of many different positions of the cursor or the probe while adjusting its position. The retention interval is not controlled in the cursor-positioning response mode. These reasons probably have prevented the adjustment method from being used more often in studies on displacement.

The probe judgment provides a less direct measure of displacement and typically requires more trials than does cursor-positioning (Hubbard, 2005). For example, displacement may be efficiently assessed with 5–10 trials of cursor-positioning, whereas 10 or more probe judgments must be obtained for each of the (usually 5–9) probe positions to assess the displacement. One should also carefully choose the procedure for assessing displacement from the obtained psychometric curves, because various procedures require normal momentary threshold distributions (see Guilford, 1954). Another problem with this method is the occurrence of context effects associated with the range of stimuli used and related biases caused by the observer's tendency to use the available responses equally often (Garner, 1954; Stevens & Galanter, 1957). Thus, an appropriate number and spacing of probe positions is desired. Unfortunately, because of the specific characteristics of each observer this goal is difficult to achieve and many pilot studies have to be performed.

Adaptive methods such as PEST, that can overcome the problem of selecting proper probe positions, were used in some studies on displacement (e.g., in Kerzel, 2003b). Other adaptive methods, such as the method of limits or its variations, e.g. the staircase method, could also be appropriate. The major drawback of these methods is their proneness to serial errors (e.g. the error due to expectation or response habituation; see Gescheider, 1997). However, in a multifactorial experiment, serial errors can be eliminated by interleaving the series measuring displacement in different experimental conditions. For example, the stimuli may be presented in the following order: A1, B1, A2, C1, B2, etc., where the letter indicates the series of stimulus intensities and the number indicates the successive number of the stimulus within the series. With many interleaved series, we minimize the probability of the observer knowing which stimulus in a certain series is currently presented. Interleaved series, therefore, prevent observers from anticipating the rule used by experimenter for presenting the next stimulus, thus reducing the sequential response bias (Jesteadt, 1980; Levitt, 1971). The staircase method, which is less time-consuming than the conventional method of limits, reduces the number of presented stimuli to the minimum by changing the direction of series (i.e. the direction of change in stimulus intensity) as soon as there is a change in response. Because one cannot operate with the whole stimulus range, the learning effect and the sequential error are minimized.

Although studies on displacement using different psychophysical methods often give convergent results, we still do not know a lot about the effect of the measurement method on the absolute value of the displacement. Only a few studies have directly compared different methods of measuring displacement. Kerzel (2003b) reported that probe judgments produced much less forward displacement than motor judgments (specifically mouse and natural pointing movements). In his study, observers were required to gaze at the fixation point throughout the trial. While adjusting the position of the cursor, observers were allowed to look at the remembered vanishing point, whereas when judging the position of the probe, they still had to look at the fixation point. Thus, the results of these methods cannot be compared directly. Therefore, we decided to allow observers in our study to make tracking eye movements so that settings during the time of response production would be as comparable as possible, even when using different methods. Moreover, other stimulus and display characteristics were matched across the methods to provide a maximally direct comparison of the displacements.

The purpose of the present study was to examine whether the magnitude of displacement is affected by the measurement method. Displacement was measured with the method of adjustment, the method of constant stimuli, and the staircase method. Since different methods of measuring displacement involve different psychological processes, it was reasonable to expect that these methods will result in somewhat different estimations of displacement.

METHOD

Participants

Eighteen undergraduate psychology students (all female, aged 19 to 24 years) voluntarily participated in the experiment. All of them had normal or corrected-to-normal vision. Participants had no previous experience with experiments in motion perception or displacement, and had no knowledge about the purpose of the experiment.

Apparatus and stimuli

Stimuli were presented on a CRT display NOKIA Multigraph 446XPRO with 85 Hz vertical refresh rate. The visible region of the computer screen (measuring 34.0 cm in width and 25.5 cm in height) subtended 19.3° × 14.5° of visual angle. A homogeneous grey background (with 29 cd m^{-2} luminance) was presented on the screen throughout the experiment.

The participants pressed the button 'Next' when ready. Five-hundred milliseconds later a small yellow square subtending a visual angle of 0.2° appeared vertically centered. Its exact horizontal position was variable. It was chosen randomly within the range of 4° ± 1° to the left or to the right of the screen centre. The square was visible for 200ms. It was used to attract attention, so that observer's attention would be directed towards the location where the target would later appear.

Five-hundred milliseconds after the yellow square has disappeared, the moving target suddenly appeared on the screen in its full width, centered at the same place where the yellow square appeared before. Target was a small red square (with 5 cd m^{-2} luminance) which subtended 0.5°. It traveled horizontally either from left to right or from right to left. It changed its position in small discrete steps rapidly, so that motion was perceptually continuous. Altogether the target traversed 8° in 1000 ms, with the average velocity of 8°/s. Equation 1 denotes target position s_i (i.e., distance traveled) at a point in time t_i.

$$s_i = v_0 t_i + \frac{1}{2} a t_i^2 \quad (1)$$

Three different constant motion accelerations were presented. Target velocity was either constant at 8°/s (in Equation 1, v_0 was 8°/s and a was 0°/s^2), was increasing linearly from 4 to 12°/s (in Equation 1, v_0 was 4°/s and a was 8°/s^2), or decreasing linearly from 12 to 4°/s (in Equation 1, v_0 was 12°/s and a was –8°/s^2).

Three-hundred milliseconds after the target has disappeared, a probe appeared on the screen close to or at the target's vanishing point. It appeared at the same vertical position as the target, but its horizontal position was either the same or different from the position of the target's disappearance. In the adjustment method, the probe appeared at a random position within the range of –0.4° to +0.8° from the target's vanishing point. In the constant-stimuli method, the probe appeared at –0.4°, –0.2°, 0.0°, +0.2°, +0.4°, +0.6°, or +0.8° from the final position of the target. In the staircase method, the value of the probe position varied up and down in steps of 0.1°, with all series starting at displacement of +0.2° from the vanishing point of the target. Positive numbers indicate displacement in the direction of the motion and negative numbers indicate displacement opposite to the direction of motion.

Procedure

The experiment was run in a dimly lit room. Participants sat facing the computer screen at the distance of 100 cm. The head was stabilized by head rest to maintain this distance at all times. Viewing was binocular. Participants had to pursue the target while it was moving, and after it had disappeared, they had to respond as instructed by the current method.

Participants were divided into three groups of 6 people. Each group received different order of psychophysical methods (the order for the first group was: method of constant stimuli – staircase method – adjustment method; for the second group: staircase method – adjustment method – method of constant stimuli; for the third group: adjustment method – method of constant stimuli – staircase method). Within each method, conditions displaying different directions of motion and accelerations were presented in random order.

In the constant-stimuli method and in the staircase method, 700 ms after the probe appeared, three buttons appeared on the screen and, by clicking the proper button, participants had to identify whether the probe appeared at the same position where the target has previously disappeared, at a forward position in the direction of motion, or at a position opposite to the direction of motion. If participants did not pay attention to the trial or have forgotten where the target has disappeared, they could choose the alternative *Once again* and the trial was repeated at a random time later in the experiment. After pressing the button *Next,* the answer was saved and immediately the next trial began. Participants could wait for as much as they wanted before responding and could rest between trials. During the experiment they received no feedback about the accuracy of their responses.

In the constant-stimuli method, 42 experimental conditions (3 motion accelerations × 2 motion directions × 7 probe positions) were randomly mixed within a block. Ten blocks of trials were presented. The session with this method was usually completed after 25–30 min. Data were analyzed using Spearman's procedure of computing an arithmetic mean of the uncumulated distributions (see Guilford, 1954). The derivative of proportion of answers *forward* and *backward* was calculated. If the psychometric curve of certain responses did not start with the proportion 0.00 or did not end with the proportion 1.00, additional extreme category of values was introduced. Proportion residual was attributed to that category and included in calculations of the forward and the backward threshold. The point of subjective equality (PSE) was determined as the average of the two thresholds. PSE was also determined as the arithmetic mean of the distribution of responses *same.*

In the staircase-method, there were 6 experimental conditions (3 motion accelerations × 2 motion directions). Two up-and-down series were run in each experimental condition. The first series was tracking the change from response *forward* to *same* or the opposite, and was measuring the forward threshold. The second series was tracking the change from response *same* to response *backward* or the opposite, thus measuring the backward threshold. The series were terminated after 10 reversals. Momentary forward and backward thresholds were calculated at the reversals (see Levitt, 1971), and momentary PSE was then calculated as their average. If the response changed directly from *forward* to *backward* (or the opposite), both thresholds and the PSE were determined as the average between the two probe positions that received different responses. Series of different experimental conditions were interleaved (12 series ran at the same time) so potential serial effects could be eliminated. Participants usually needed 200 to 300 trials (approx. 15 min) to finish this part of the experiment.

In the method of adjustment, after the probe appeared on the screen, observers adjusted the position of the probe to the point of target's disappearance by pressing designated buttons. They used four numerical keys: *4* and *6* for gross position changes to the left or to the right, and *1* and *3* for detailed adjustment. They were instructed not to look away from the screen during responding. Sixty trials were presented, 10 per experimental condition. This part of experiment usually took 5 minutes. Adjustments were analyzed separately for each condition. Experiments with all three methods were completed in a single session, with short intermediate breaks. At the beginning of the session, participants read general instructions written on the paper. Before performing the experiment with a certain method, they went through a short training under the supervision of the experimenter who explained the procedure once again, showed how responses should be made, answered questions if asked, and finally monitored the training (without any feedback), during which participants learned how to use the computer mouse or keyboard buttons. Experimenter then left the room and returned when the experimental part with a certain method was over to continue with the next experimental part (the next method).

RESULTS

A significance criterion of $p < .05$ was used for testing hypotheses. First, we examined whether two different ways of calculating PSE in the method of constant stimuli gave different results. Namely, PSE was determined either as the average of the forward and the backward threshold or as the arithmetic mean of the distribution of the proportion of responses *same.* Table 1 shows the average values of PSE obtained in the two procedures and the result of the *t*-test for dependent samples by which the significance of the difference between the two PSEs was evaluated.

Since the difference of PSEs estimated by two procedures was not significant, we decided to examine the PSEs derived with the first procedure, i.e., from the distributions of responses *backward* and *forward,* for they include more responses than the distribution of responses *same* (when responses of different types were summed across the observers, 2370 responses *backward,* 2434 responses *same,* and 2327 responses *forward* were obtained). The absence of differences between the two procedures of estimating PSE indicates that the positions of the probes were chosen appropriately and that the distributions of responses *forward* and *backward,* as well as the distribution of responses *same,* were close to being symmetric around PSE.

Table 1

Points of subjective equality as calculated with two different procedures within the constant-stimuli method, and significance of the difference between the two values

Experimental condition	$PSE_{backward,forward}$	PSE_{same}	result of *t*-test
Decelerated – To the right	9.13	9.89	$t\,(17) = -0.99, p = .33$
Decelerated – To the left	7.06	6.61	$t\,(17) = 0.90, p = .38$
Constant velocity – To the right	12.73	12.94	$t\,(17) = -0.19, p = .85$
Constant velocity – To the left	9.71	9.06	$t\,(17) = 1.14, p = .27$
Accelerated – To the right	12.98	14.11	$t\,(17) = -1.48, p = .16$
Accelerated – To the left	8.99	9.22	$t\,(17) = -0.22, p = .83$

Note. In the first procedure, $PSE_{backward,forward}$ was calculated as the average of the backward and the forward thresholds, which were determined as the arithmetic mean of the uncumulated distribution of the proportion of responses *backward* and *forward*. In the second procedure, PSE_{same} was calculated as the average of the distribution of the percentage of responses *same*.

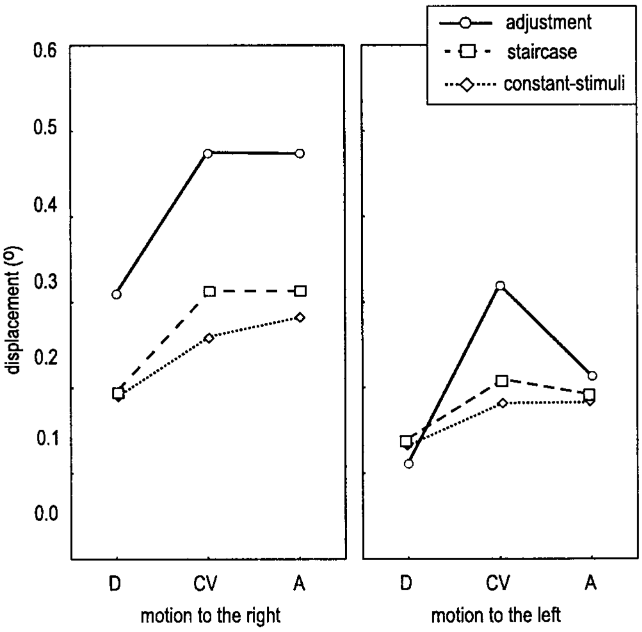

Figure 1. The average displacement in different experimental conditions (with target moving either to the right or to the left with deceleration–D, constant velocity–CV, or acceleration–A) as measured with three psychophysical methods: the method of adjustment, the constant-stimuli method, and the staircase method.

Figure 1 shows the average displacement in the conditions with three different psychophysical methods. In all of the experimental conditions, the average displacement of the remembered final position of the moving target was in the direction of motion. For example, when the target moved from left to right, the remembered vanishing point was to the right of the actual vanishing point, and when the target moved from right to left, its remembered vanishing point was to the left of the real vanishing point.

Although forward displacement was obtained with different methods of data gathering, the magnitude of displacement was not uniform across the conditions. To compare the results of different methods and to examine the effects of other factors, PSEs were entered into a three-way repeated-measures analysis of variance (psychophysical method × acceleration × direction of motion). Whenever the assumption of sphericity (estimated by Mauchly's test) was violated, the Greenhouse-Geisser correction was used.

Displacement was larger with the target moving from left to right ($M = 0.313$, $SE = 0.031$) than with the target moving from right to left ($M = 0.187$, $SE = 0.037$), $F\,(1, 17) = 9.98, p < .01$, $MSE = 0.130$. In the constant-stimuli method displacement increased with acceleration, whereas in the staircase method and the adjustment method displacement increased from decelerated to constant-velocity motion but later decreased for accelerated motion, and more so for the adjustment method (see Figure 1). Ignoring motion direction, the difference between the methods was smaller in the deceleration conditions than in the constant-velocity and the acceleration condition, $F\,(2.92, 49.64) = 4.94, p < .01$, $MSE = 0.011$. The main effect of motion acceleration was also evident, $F\,(2, 34) = 20.20, p = .000$, $MSE = 0.020$. Overall, the smallest displacement was obtained, as expected, with decelerated motion ($M = 0.181$, $SE = 0.025$). Displacement in conditions with constant-velocity motion ($M = 0.293$, $SE = 0.031$) was on the average slightly higher than displacement in conditions with accelerated motion ($M = 0.276$, $SE = 0.033$). This result was surprising, for some previous studies (e.g., Finke et al., 1986; Poljanšek, 2002) reported the largest displacement with the accelerated motion, followed by displacement for constant-velocity motion, and the smallest displacement for decelerated motion.

Figure 1 shows the main effect of the psychophysical method. The method of adjustment resulted in a larger displacement ($M = 0.318$, $SE = 0.046$) than the method of constant stimuli ($M = 0.206$, $SE = 0.025$) and the staircase method ($M = 0.226$, $SE = 0.026$), $F\,(0.50, 25.56) = 6.15, p = .011$, $MSE = 0.083$. Pair-wise comparisons of the means (Scheffe test) showed statistically significant difference between the adjustment method and the constant-stimuli method ($p < .01$) and between the adjustment method and the staircase method ($p < .05$), whereas the difference between the constant-stimuli method and the staircase method was not significant ($p = .85$). Therefore, with the constant-stimuli method and the staircase method we obtained com-

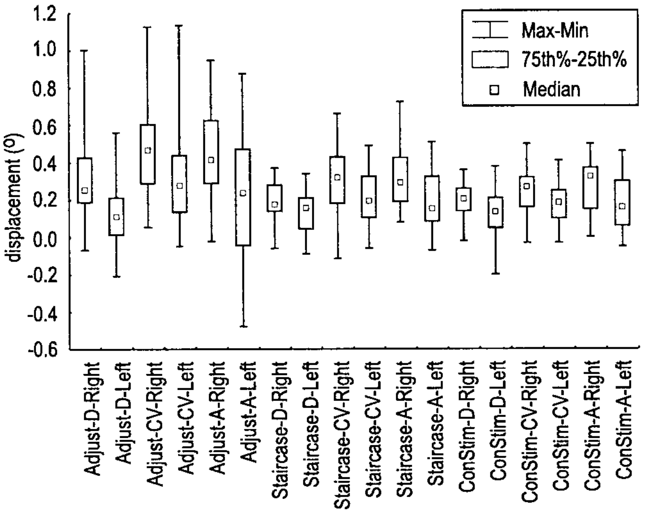

Figure 2. Variability of PSEs obtained in different experimental conditions with three psychophysical methods. Box-plots are named according to the psychophysical method (Adjust–the adjustment method, Staircase–the staircase method, ConStim–the constant-stimuli method), motion acceleration (D–decelerated motion, CV–constant-velocity motion, and A–accelerated motion), and motion direction (Right–motion from left to right, and Left–motion from right to left). Whiskers show the range and boxes show the interquartile range of individual average displacements.

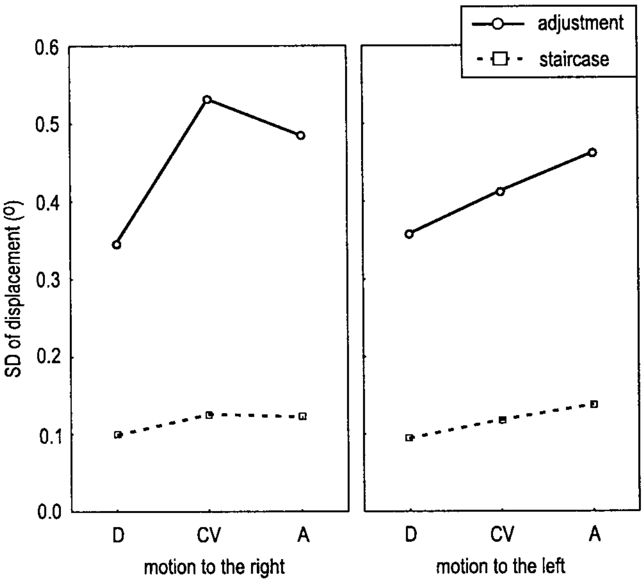

Figure 3. Comparison of average *SD*s of displacements within participants in the adjustment method and the staircase method, obtained in different experimental conditions (target was moving either to the right or to the left with deceleration–D, constant velocity–CV, or acceleration–A).

parable displacements, whereas the results obtained with the adjustment method differed from the results of the other two methods.

In the next step we examined the variability of PSEs gathered with different methods. First, we examined the variability across observers. Figure 2 shows the variability of average PSEs obtained in different experimental conditions with the three methods. As can be seen, the inter-individual variability was largest in the adjustment method, whereas in the staircase method and in the constant-stimuli method it was comparable and smaller.

To examine the internal consistency of different methods two separate comparisons had to be done. Whereas in the adjustment method and the staircase method every adjustment or every run in a series gives a result (a temporary PSE), in the method of constant stimuli only one general PSE can be obtained. Therefore, we first compared the adjustment method and the staircase method. Because 10 results were obtained within each experimental condition for each participant, the intra-individual variability of PSEs gathered with the two methods could be examined. For each experimental condition and for each participant separately, we compared a standard deviation of 10 adjustments obtained with the adjustment method and a standard deviation of PSEs obtained with the staircase method in 10 series directions. Standard deviations averaged across the participants are shown in Figure 3. Average *SD* of PSEs obtained with the staircase method was approximately four times lower than average *SD* of PSEs obtained with the adjustment method. It is clear that the adjustment method has lower internal consistency than the staircase method.

While adjusting the position of the probe, the traces of the adjustments could have interfered with the remembered final position of the target (i.e., the masking effect could have occurred). The memory trace of the target's final position could have been attracted toward the probe or repulsed away from it. To examine whether the probe had any effect on the displacement, we aggregated data of all observers and calculated the mean displacement within different categories of the initial probe position. Figure 4 shows the results, separately for the motion to the right and for the motion to the left. For example, when the target was moving to the right and the probe appeared somewhere between 0.2° and 0.4° left of the actual vanishing point of the target, the average displacement was 0.6° in the direction of the motion. Thus, the more the initial probe position overshot the actual vanishing point of the target, the smaller the displacement was, and vice versa. Especially for motion to the left it is interesting to note that when the probe was initially presented at a position further down in the direction of motion compared to the position of average displacement, the adjusted position of the probe was closer to the actual vanishing point of the target, and when the probe was initially

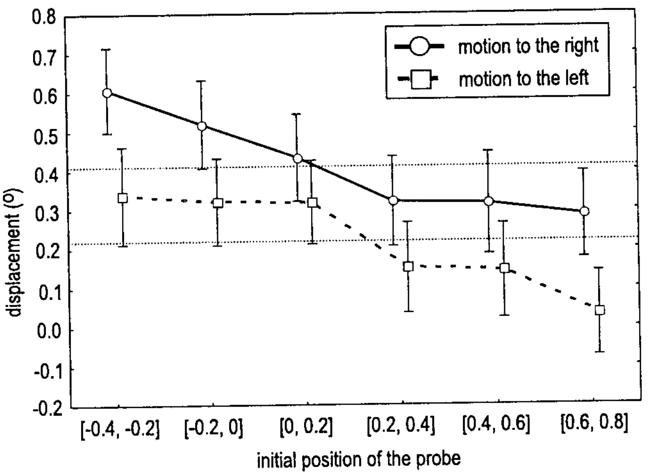

Figure 4. The effect of the initial probe position on the magnitude of displacement. Initial probe positions were grouped into seven categories. Displacements obtained within each category of the initial probe position were averaged across all the observers. The dotted horizontal lines indicate the overall average displacement for motion to the right (upper line) and for motion to the left (lower line). Vertical bars denote 95% confidence intervals.

Table 2

Comparison of the uncertainty intervals as determined by the staircase method and the constant-stimuli method

Experimental condition	Staircase method		Constant-stimuli method		result of t-test
	M	*SD*	*M*	*SD*	
Decelerated – To the right	0.21	0.12	0.24	0.10	1.30
Decelerated – To the left	0.20	0.10	0.25	0.09	3.15*
Constant-velocity – To the right	0.16	0.09	0.24	0.10	4.33**
Constant-velocity – To the left	0.18	0.14	0.24	0.11	1.88
Accelerated – To the right	0.16	0.14	0.24	0.10	3.09*
Accelerated – To the left	0.18	0.18	0.24	0.11	1.90

Note. *df* = 17
***p* <.001; **p* <.01.

presented closer to the actual vanishing point compared to the position of average displacement, the adjusted position of the probe was much further in the direction of motion. It, therefore, appears as if the observers overshot their adjustments while relocating the probe from its initial position to the remembered position of target's disappearance.

Finally, the uncertainty intervals in the staircase method and the constant-stimuli method were compared. The uncertainty interval can be determined in the two probe-judgment methods, contrary to the adjustment method where only a PSE can be defined with each adjustment. The uncertainty interval is the difference between the forward and the backward threshold and is an indicator of the range within which the probe position is perceived as being the same as the target's vanishing point. For each experimental condition only a single forward and backward threshold can be determined in the constant-stimuli method, whereas 10 thresholds of each type were obtained with the staircase method. Therefore, averaged staircase-method thresholds were compared to the values gained with the constant-stimuli method. Table 2 shows descriptive statistics for the uncertainty intervals in the two methods and the results of the paired-samples t-tests with which the differences between the two measures were tested. We can see that the staircase method produced slightly smaller uncertainty intervals in all experimental conditions (in most conditions the difference also reached statistical significance).

DISCUSSION

In our study we examined the effect of response measures on displacement. Some of the results deserve a comment before we continue with the analysis of the psychophysical methods' validity for measuring displacement.

The overall magnitude of displacement was around 0.25°. This result is comparable to displacements obtained in other studies. Poljanšek (2002) obtained slightly smaller displacements when a larger target and smaller velocities were used. Hubbard and Bharucha (1988) used much larger velocities and found displacements as big as 2.5ş. Kerzel (2000) used larger constant motion velocity (18.75°/s) and longer retention interval (500 ms) and obtained a displacement of 1.4°. Hubbard and Motes (2002) found displacements similar to ours in conditions where size and velocity of the target were comparable. Therefore, the magnitude of displacement in our study seems to properly fit within the values obtained in previous studies with different stimulus and display characteristics.

Various factors can affect the displacement magnitude of the simple target moving with constant velocity. Memory shifts increase in size as the velocity and acceleration of motion increases (Finke et al., 1986; Poljanšek, 2002). An unexpected swap in the order of the magnitude of displacement in conditions with different acceleration (Figures 1 and 3) is difficult to explain, but it occurred in almost every participant. Smaller displacement in conditions with accelerated motion might be a consequence of a relatively high speed of a small target at the end of such motion (cf. Munger & Owens, 2004; Kerzel, Jordan, & Müsseler, 2001), where target position might not be represented well because of

(a) the perceptual limitations, (b) the limitations in smooth pursuit of accelerating motion (see Watamaniuk & Heinen, 2003), or (c) the higher rate of decay of the displacement at faster velocities (see Freyd & Johnson, 1987; Hubbard & Bharucha, 1988).

Considering the effect of the motion direction–displacement was larger for the motion to the right than for motion to the left–this finding is consistent with what was observed in some previous studies (e.g., Faust, 1990; Halpern & Kelly, 1993; Hubbard & Bharucha, 1988, Exp. I; Kerzel, 2003a; Poljanšek, 2002). It seems that motion direction has an effect on displacement (although not consistently across different studies; see Hubbard, 2005). The direction effect may be explained by the left-right asymmetries in visual processing (Halpern & Kelly, 1993), i.e., by the larger attentional span and better attentional tracking towards right (Kerzel, 2003a). Due to our everyday reading experience, we may be more used to extrapolating and predicting patterns and content in the right part of the visual field, and so displacement for motion to the right is bigger than displacement for motion to the left. Nevertheless, the results of the three methods revealed similar patterns for both motion directions.

Adjustment method vs. probe judgments

The adjustment method yielded larger and more variable displacements than the constant-stimuli method and the staircase method. However, larger and more variable measures of sensitivity are not an inherent property of the adjustment method. Studies comparing different psychophysical methods with some other phenomena, e.g., Müller-Lyer illusion (McKelvie, 1984), temporal hearing threshold (Plattsmier & McFadden, 1988), color discrimination (Siegel, 1962), and frequency discrimination (Wier, Jesteadt, & Green, 1976) gave equivocal conclusions about the disadvantage of the adjustment method in terms of the session-to-session variability and the congruency of its results with the results of other methods. It seems that the method of adjustment is not generally inferior to the other two methods and that its appropriateness depends on the sensory modality and specific properties of the studied phenomenon. We will now present several possible reasons why it could have been less valid in the context of our study.

There were several differences between the adjustment method and the two probe-judgment methods that could have caused the displacement in the adjustment method to be larger than in the other two methods. First, the temporal interval between the target offset and the observer's response (i.e., response latency) was typically longer in the adjustment method. Previous studies discovered that forward displacement increases with retention interval (i.e., the temporal interval between the target offset and the onset of the probe) and is the largest around 250 ms after the target disappears (Finke & Freyd, 1985; Halpern & Kelly, 1993; Kerzel, 2000; see also Hubbard, 2005), while afterwards it remains at the same level (Kerzel, 2000) or decreases (Freyd & Johnson, 1987). Decrease in the forward displacement was attributed to memory averaging. In our study, however, the difference between the methods cannot be attributed to memory averaging because displacements would presumably have to decrease with increases in response latencies. This means that the adjustment method should have yielded smallest displacements, which was clearly not the case (see Figure 1). Larger displacements obtained with the adjustment method would perhaps be better explained with the distinctive response mode used in this method. Responding in the adjustment method involved motor functions that were not present in the probe-judgment methods. Kerzel (2003b) who obtained similar results when comparing pointing and probe-judgment, argued that such results support the notion of distinct processes serving motor actions and cognitive judgments. The motor system extrapolates future positions to a larger degree than the visual system in order to overcome the processing delays of the visual system. When in our study the position of the probe had to be adjusted to the remembered final position of the target, it is possible that observers employed additional motor processes, although they actually did not have to point to the location of the remembered vanishing point. Perhaps the active response mode, whatever its manifestation, automatically yields larger displacements than the passive (non-motor) response mode, which involves only a comparison of two locations and is characteristic of the probe-judgment methods.

The larger variability of displacements obtained with the adjustment method may be related to the complexity of the task. In the adjustment method, the observers had to hold the final position of the target in the memory while updating the location of the probe. The latter required the coordination of many activities: operating the keyboard buttons, monitoring the current position of the probe, and comparing this position with remembered final position of the target. In comparison to the probe judgment, besides motor processes mentioned previously, the task also introduced a notable attentional load and required mobilization of additional memory resources. Individual differences in the mentioned processes, as well as the differences in the speed of adjustment (leading to different levels of preserving memory trace of the target) could have contributed to the large variability of the results.

Another shortcoming of the method of adjustment as used in our experiment is the apparent dependence of its results on the initial probe position. When the initial position of the probe overshot the true displacement in the observer, the adjusted final position of the probe was closer to the actual vanishing point of the target, and inversely, when the initial position of the probe undershot the displacement, the adjusted final position resulted in a larger estimate of displacement in the direction of motion. The further away the probe appeared from the remembered target position, the greater was the distance the probe traversed during the adjustment, which probably also resulted in the longer duration of the adjustment process. One can assume that increased response latency (i.e., the time between the offset of the target and the end of the adjustment process) leads to a higher probability that the memory of the vanishing point will be distorted. The effect of the initial position of the probe on the obtained displacement may thus indicate that (i) during the adjustment process, the remembered vanishing point of the target was repulsed away from the probe, or (ii) there was a response habituation present (a motor error typical for the adjustment method) and the adjustment overshot the actual (initial) observer's displacement. No matter which explanation is correct, the effect of the initial probe position calls attention to the fact that the results of the adjustment method depend on the initial position of the probe. It is highly possible that in studies using cursor positioning the results will depend on the initial position of the cursor. Moreover, even in studies using pointing of the initial position of the hand might play an important role.

Method of constant stimuli vs. staircase method

The 3-response alternative of the constant-stimuli method (using responses *forward*, *same*, *backward*) and the staircase method with two series within each experimental condition (the backward and the forward series) produced comparable displacements.

Because estimated PSEs obtained with the staircase method had a similar magnitude and variability as the ones obtained with the constant-stimuli method, it can be concluded that the staircase method can efficiently replace the more time-consuming method of constant stimuli when displacement is to be evaluated.

The staircase method produced smaller uncertainty intervals than the method of constant stimuli. This could indicate that observers set more liberal decision criterion when performing the experiment with the first method. In the method of constant stimuli, the whole transition zone from a clearly backward probe position to a clearly forward probe position was covered successfully for most of the participants, so that some positions evoked very clear sensations of the shift in probe position compared to the remembered vanishing point of the target. The three types of responses were chosen equally often. In the staircase method, on the other hand, probe positions were usually chosen close to the forward and the backward threshold values, and the comparison of the remembered target's vanishing point and the probe position was much more ambiguous and uncertain. Because two series per condition were presented at the same time, we can assume that the answer *same* was chosen approximately twice as often as the other two answers. A more liberal criterion was perhaps set to obtain at least some *forward* and *backward* responses, and thus the forward and the backward thresholds were smaller than in the constant-stimuli method. Still, as decision criterion affects only the uncertainty interval, but has no effect on the magnitude of displacement, we can assume that both probe-judgment methods can be used with equal confidence when only the size of the displacement is to be examined.

CONCLUSIONS

Which method gave the most valid assessment of displacement? Unfortunately, the results of other studies on displacement cannot serve as external validity criteria for displacements obtained with different methods in our study, because our experimental conditions were not exact replicas of those used in other studies. Different studies are usually difficult to compare, not only because of explicit differences in experimental conditions related to the measured phenomenon (such as, for example, target velocity in the case of displacement), but also due to the possible effects of social factors and subtle differences in laboratory settings (see Orne, 1962). It is therefore very difficult to assess the validity of a certain method through a comparison of the absolute magnitudes of displacement obtained in different studies. Instead, the best indicators of the validity of the methods seem to be (a) the convergent validity of the methods applied in a single study, while holding the experimental conditions constant, and (b) the stability of the results, i.e., their variability within an observer. According to these criteria, our study showed a clear advantage of the probe-judgment methods over the adjustment method when displacement is to be measured. Further insights into the appropriateness of different methods for measuring this phenomenon could perhaps be attained through replicating the experiment and studying methods' test-retest reliability.

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