# Investigating Spatial Reference Systems through Distortions in Visual Memory

Steffen Werner and Thomas Schmidt

Institute of Psychology, University of Göttingen, D-37073 Göttingen, Germany
`{swerner,tschmid8}@uni-goettingen.de`

**Abstract**. Memory representations of spatial information require the choice of one or more reference systems to specify spatial relations. In two experiments we investigated the role of different reference systems for the encoding of spatial information in human memory. In Experiment 1, participants had to reproduce the location of a previously seen dot in relation to two landmarks on a computer screen. The placement of the two landmarks was varied so that they were horizontally or vertically aligned in half of the trials, and diagonally aligned in the other half of the trials. Reproductions showed a similar pattern of distortions for all four different orientations of the landmarks, indicating the use of the landmarks as an allocentric reference system. In Experiment 2, the influence of this allocentric reference system for very brief retention intervals (100 and 400 ms) was demonstrated in a visual discrimination task, extending previous work. The results suggest that landmark-based spatial reference systems are functional within 100 ms of stimulus presentation for most of the observers. Allocentric reference sytems therefore are an essential part even of early mental representations of spatial information.

## 1 Introduction

Whenever we try to communicate the location of an object to another person, we must present a reference system in which the location is specified. Different types of such reference systems exist, as many authors have pointed out (e.g., Klatzky, 1998; Levinson, 1996). For example, we can use ourself or another external object as the referent. This basic distinction pits an egocentric, or body-centered reference system against an allocentric, or environment-centered reference system (Klatzky, 1998). It is often important to make clear which reference system is used in the current course of communication. During a medical examination, for example, the phrase "raise your left foot" might lead to confusion because it is not clear whether it is meant from the doctor's or the patient's point of view (i.e., a conflict of different egocentric reference systems). Although the use of different reference systems might be most obvious in the course of communication, reference systems are as much required in nonverbal situations. To remember the location of an object, for example, we have to know the reference system used at encoding, just as partners in communication must know which reference system the other one is currently using.

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In many perceptual and memory systems, spatial reference systems are hard-wired and cannot be easily changed. In visual perception, for example, different reference systems are used at different stages of processing. Whereas all information is initially encoded in a retinocentric reference system, the information is later represented in head-centered coordinates and eventually transformed into effector-specific coordinates, e.g., the location of an object relative to one's hand if one plans to grasp it (e.g., Berthoz, 1991; Soechting & Flanders, 1992). Of course many of these representations may exist in parallel. In contrast, the reference systems used in spatial memory and verbal communication are much more varied and flexible (see, for example, the overview in Levinson, 1996).

### 1.1 Investigating Spatial Reference Systems

There are a number of different methods used to probe the spatial reference systems used in human spatial memory. Linguistic analyses of spatial descriptions are one way to assess the reference system used to describe spatial relations. To increase the amount of control, linguistic acceptability ratings are often used. Observers in such studies are asked to rate the appropriateness of a verbal description of a real or depicted situation (see Levelt, 1996, for some examples). If the spatial configurations and the verbal descriptions are carefully chosen, the ratings will indicate which reference system the observers preferred. A different attempt to investigate the role of spatial reference systems in linguistic studies relies on the analysis of reaction times and relative error rates when judging the correctness of verbally presented spatial expressions. In one such study, Carlson-Radvansky and Jiang (1998) used the effect of negative priming to study the activation of multiple reference systems when judging spatial relations. They were able to show that a reference system available but not used in a prior task was more difficult to use in a following task than when the reference system was not available in the prior task. This suggests that the reference system not used in the prior task was nevertheless activated, even though it was of no relevance to the task at hand.

When investigating the spatial reference systems used in human memory, however, linguistic studies have one critical drawback. Spatial memory, in these cases, is accessed not directly but mediated by verbal processing at some stage. This leaves open the possibility that the reference systems observed might not reflect any of those used in spatial memory, but rather the reference systems used in language to express spatial relations. A number of non-verbal methods have therefore tried to investigate spatial reference systems without intervening verbal processing.

Several recognition or reproduction tasks have been used for this purpose. Pederson (1993), for example, had observers look at a configuration of objects on a table. They then had to turn around to face another table, which had been standing directly behind them. Their task was to reconstruct the configuration as they remembered it. Most people who were brought up in a western culture reconstructed the layout so that it matched their remembered, egocentric image (e.g., the object on the left in egocentric terms was again the object on the left in egocentric terms). Participants from cultures using mainly cardinal directions to indicate spatial relationships, however, tended to place the objects so that their cardinal relations stayed the same (e.g., the northern object was again placed on the northern end of the new table, the eastern object to the East, etc.), thus mirror-reversing the egocentric relations. Although verbal coding of the spatial relations might still be a factor in this type of study, it was not explicitly required as in the other studies mentioned above.

A different non-verbal approach to probing the reference systems used in spatial memory relies on the effect of orientation-specificity (Presson & Hazelrigg, 1984). A spatial behavior is termed orientation-specific whenever some part of it critically depends on the real or imagined orientation of the agent. A simple example of this is the use of map knowledge. It is commonly assumed that the orientation of a map, which is usually North-up, corresponds to the main reference-axis used in spatial memory for large-scale spaces (e.g., Sholl, 1987). Therefore, if a person is asked to imagine standing in Rome, facing Oslo, pointing in the direction of Madrid, this is usually an easier task than imagining standing in Madrid, facing Rome, pointing to Oslo. The reason for this is that the Rome-Oslo axis coincides with the North-South reference axis in spatial memory and is therefore easier to imagine. In a number of recent studies, this effect has been used to investigate the role of different kinds of reference systems (Roskos-Ewoldsen, McNamara, Shelton & Carr, 1998; Shelton & McNamara, 1997; Sholl, 1987; Werner, in preparation; Werner, Saade & Lüer, 1998; Werner & Schmidt, in press).

The approach which we will focus on in this paper relies on distortions in spatial memory as an indicator of the reference system used (e.g., Huttenlocher, Hedges, & Duncan, 1991; Laeng, Peters, & McCabe, 1998). A large body of psychological research shows that people often err systematically when remembering spatial locations. These distortions in spatial memory are commonly seen as evidence that perceived space is structured in some way, e.g. by different regions, groupings etc., which biases the way in which locations are remembered. The perceived structure partly determines the available reference systems. A simple example will illustrate this point. When observers see a dot together with two landmarks, as depicted in Figure 1, they show a systematic pattern of errors (Werner & Diedrichsen, submitted). Dot locations close to the two landmarks and the midpoint between the landmarks are reproduced further away from these points than they really are, exaggerating small deviations. Similarly, locations directly above or below the horizontal line connecting the two landmarks are usually reproduced further above or below. Other dot locations, such as the one right on the landmarks or the midpoint, are reproduced without bias. Memory for the dot location is thus tied to the two landmarks as the basic elements of the reference system.

There are a number of advantages of using the analysis of spatial memory distortions as an indicator of spatial reference systems. The non-verbal character eliminates the potential problems associated with verbal tasks or responses as was mentioned above. It also makes this procedure viable for studies with pre-verbal children (e.g., Huttenlocher, Newcombe & Sandberg, 1994) or even animals. A third advantage lies in its potential for comparing different actions or effectors on similar spatial tasks, such as reproducing a location on a small piece of paper, pointing to it, or walking to it on a field (Werner, Saade, & Lüer, 1998).

Finally, the time course of spatial distortions in memory can be traced by using a visual discrimination method instead of a location production method. In a previous experiment in our laboratory (Werner & Diedrichsen, submitted), observers first viewed the two landmarks together with the target dot on a computer screen. After 200 ms the two landmarks and the dot disappeared and were masked by random line patterns for a variable masking interval of 100 ms to 800 ms. After this time, the two landmarks and the dot reappeared and the observers had to judge whether or not the dot had moved. On some trials the dot remained in the original location, on some others it changed its location in one of two directions. The main result was a bias of the observers towards reporting no changes when the dot had changed its location in the direction of the memory distortion, whereas more changes were reported when it had changed in the opposite direction.

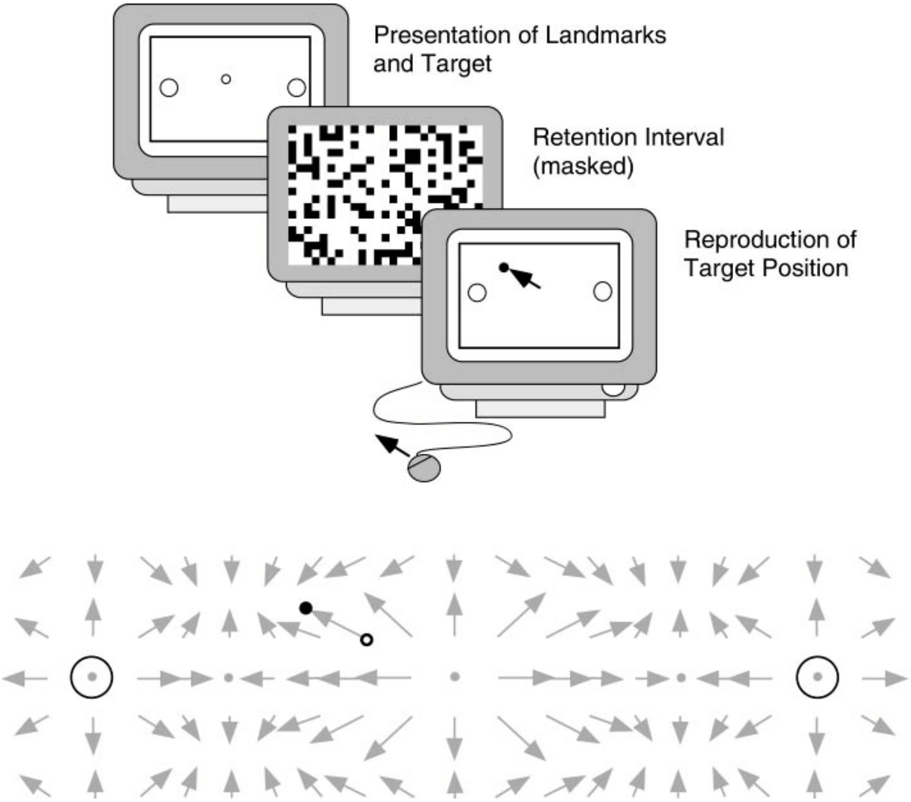

**Fig. 1.** *Top:* The two-landmarks reproduction paradigm. The observer has to reproduce the presented location after a retention interval with a mouse (the presented location is depicted as an open circle, the reproduction as a filled circle). *Bottom:* Schematic depiction of the observed distortion pattern. The arrows originate at the presented location and end at the reproduced location (based on data from Werner & Diedrichsen, submitted)

This asymmetry in responses was observable after only 100 ms, and did not increase any further after 400 ms. These results suggest that spatial memory is already distorted after retention intervals of only 100 ms and that the distortion reaches an asymptotic maximum level after less than half a second. This also indicates that spatial relations are encoded in allocentric reference systems at early stages of processing.

In this paper, we will extend the findings of Werner and Diedrichsen (submitted) by investigating the landmark-based reference system involved in the course of spatial information processing for a simple spatial arrangement, namely the location of a dot in relation to two horizontally aligned landmarks as depicted in Figure 1. In Experiment 1 we analysed the pattern of spatial distortions by asking participants to reproduce the location of the dot in relation to the two landmarks after a 400 ms retention interval. By changing the orientation of the stimulus configuration we controlled for effects of other potential reference systems. In Experiment 2, we used several of the previous targets to study the time course of their distortion in a visual discrimination task.

## 2 Experiment 1

In previous experiments, the two-landmarks configuration had only been used in horizontal or vertical orientations. This intrinsic stimulus orientation coincides with other reference systems that might possibly be used by the participants (e.g., the edges of the monitor, the direction of gravity, or the vertical and horizontal retinal axes). Experiment 1 was designed to assess whether misalignment of the intrinsic stimulus orientation with these frames of reference would change the distortion pattern. We used a total of 13 target positions between the two landmarks where we expected especially salient effects of distortion due to previous results (Werner & Diedrichsen, submitted). In one condition, the two landmarks were horizontally or vertically aligned, whereas in a second condition the whole configuration of landmarks and targets was rotated by 45°, resulting in two diagonally aligned landmark configurations. All stimuli were presented within a rectangular frame that was aligned with the monitor's sides (and thus also the gravitational axis) regardless of the condition. The experimental task was simply to reproduce the exact location of a briefly presented target with respect to the two landmarks.

### 2.1 Method

*Participants.* Six undergraduate students (age 23 to 31, all female, all right-handed) of the Institute of Psychology at the University of Göttingen participated for course credits or for a payment of 15,- DM per hour. Their vision was normal or corrected-to-normal.

*Apparatus.* The experiment was controlled by a Personal Computer with an AMD K-2 processor (300 MHz). Stimuli were presented on a 14" VGA color monitor (640 by 480 pixel [px]), synchronized with the monitor retrace rate of 60 Hz. Participants were seated on a height-adjustable chair at a distance of approximately 100 cm.

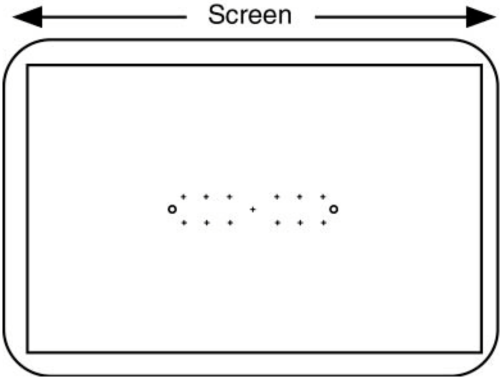

**Fig. 2.** Display configuration in Experiment 1 in the horizontally aligned condition. Stimuli are drawn to scale and were presented bright against a dark background. All thirteen possible target locations are depicted, but only one was presented at any given trial

*Stimuli.* All stimuli were presented within a white rectangular frame (600 x 380 px, 17.16° x 10.86°) at the center of the screen against a black background (Fig. 2). Landmarks were two green unfilled circles, 9 px (.26°) in diameter and 100 px (2.86°) away from the center of the screen. The target was a small white dot with a diameter of 3 px, presented at one of 13 possible locations. Landmarks and target could appear in any of four orientations. In the situation where the two landmarks were horizontally aligned (0° orientation), one of the possible locations was at screen center, the other 12 at y-coordinates of ±15 px and x-coordinates of ±90, ±60, and ±30 px. For the 90° orientation, the x- and y-coordinates were exchanged. The diagonally aligned condition ( 45° and 135° orientations counterclockwise) resulted from rotating the two landmarks and the corresponding targets around the center of the display. The frame and the mask remained unrotated. A dynamic pattern similar to static interference on a television screen that filled the rectangular frame was used. It consisted of randomly chosen black and white elements (2 x 2 px), with one quarter of the elements white at any given time. Four different random patterns were presented in succession for 33 ms each, after which the sequence repeated itself.

*Procedure.* Each trial began with the presentation of the two landmarks within the white frame. After 500 ms, the target appeared at one of the five possible locations and remained on the screen for 500 ms before it was replaced by the dynamic mask for 400 ms. The landmarks remained visible until the participant responded and were also visible during the masking interval. The participants' task was to use the mouse cursor (which looked exactly like the target) to reproduce the target's location as exactly as possible and to press the left mouse button when finished. The mouse cursor appeared randomly in the center of one of the landmarks to prevent the use of the initial cursor position as an additional spatial referent. The button press elicited a 1000 Hz, 100 ms tone. After an intertrial interval of 500 ms, a new trial began. The instruction emphasized accuracy rather than speed.

Stimulus conditions were counterbalanced such that each combination of target position and stimulus orientation occured randomly and equiprobably, with each combination appearing once every four blocks. The center target position appeared twice as often as any other target position to yield equal numbers of observations for all x and y coordinates.

Each participant performed one session of 20 blocks with 28 trials each. The session started with an additional practice block of 28 trials. After each block, participants received summary feedback of their average euclidean deviation from the target. After the session, participants were debriefed and received an explanation of the purpose of the experiment.

## 2.2 Results

For the following analyses, response times shorter than 100 ms and longer than 6000 ms were excluded (2.14 %). We also excluded all trials where responses were more than 30 px (0.86°) away from the original target (0.24 %). Additionally, we excluded all trials where the deviation from the true target was more than three standard deviations larger or smaller than the individual average target deviation (0.95 %). Practice blocks were not analysed.

Deviations of the participants' responses from the original targets were analysed with three-factorial ANOVAs (Target Position × Display Orientation × Participant). Distortions along the x- and y-axes were analysed seperately. There were no significant differences or interactions between the two different orientations in each condition. The data were therefore collapsed over these pairs of orientations. For simplicity, we will generally not report effects associated with the participant factor.

Results are shown in Fig. 3. As expected, there was a distortion of responses away from the nearest landmark and away from the midpoint between the landmarks, with smaller distortions at the midpoint itself or distant from the landmarks and midpoint. The main effect of target position on spatial distortion was significant for the x coordinate, $F(6, 30) = 3.96$, $p = .005$, as well as for the y coordinate, $F(2, 10) = 9.65$, $p = .005$. There was no main effect of display orientation, i.e. the two diagonal display orientations showed the same average distortion as the two other orientations, $F(1, 5) < 1$ for the x coordinates, $F(1, 5) = 1.71$, $p > .200$ for the y coordinates. However, patterns of distortion differed slightly across display orientations: There was an interaction of target position and orientation for the x coordinates, $F(6, 30) = 2.45$, $p < .050$, but it was not significant for the y coordinates, $F(18, 90) = 2.12$, $p = .100$. The most salient difference between display orientations is the reduced distortion for the diagonal orientations at the targets closest to the landmarks (both $p < .005$ in *post hoc* Tukey tests).

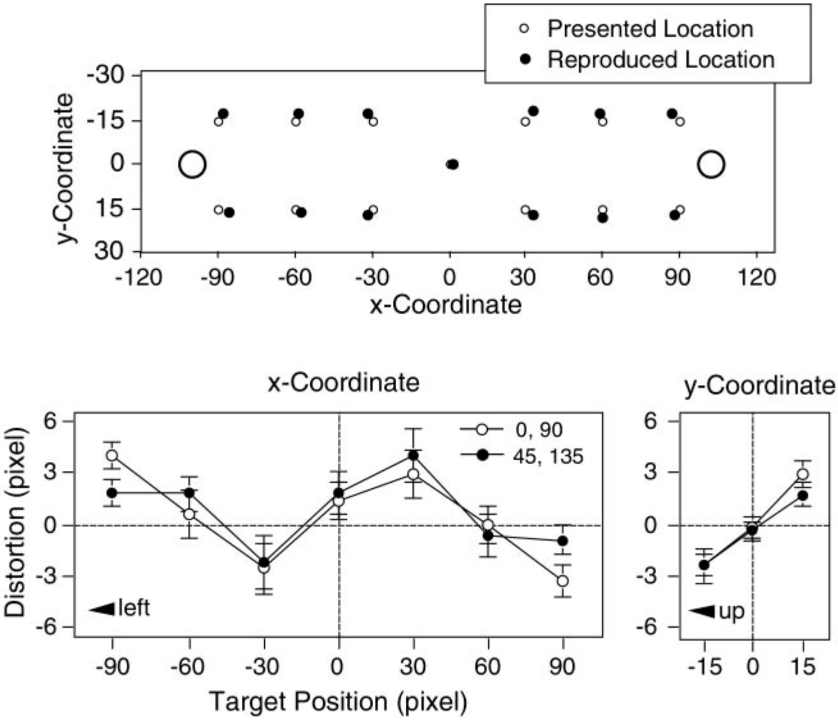

**Fig. 3.** *Top:* Presented and reproduced target locations in Experiment 1 with respect to the two landmarks (large circles). The rectangular frame does not correspond to the frame presented during the experiment. *Bottom:* Amount of distortion for x- and y-dimension separately

## 2.3 Discussion

Experiment 1 shows that visual memory is spatially distorted (Huttenlocher, Hedges, & Duncan, 1991; Laeng, Peters, & McCabe, 1998; Nelson & Chaiklin, 1980) and the results replicate the typical pattern in the two-landmarks task (Werner & Diedrichsen, submitted). The reproduced locations are distorted away from the landmarks and from the midpoint between the landmarks. This pattern is similar for different display orientations, indicating that distortions develop within an allocentric reference system defined by the two landmarks. By changing the location or alignment of different reference systems, as was done in this experiment, spatial distortion patterns can thus nicely identify the dominant reference system used to encode spatial relations in memory.

One possible reason why the distortions are smaller than expected for targets close to the landmarks at diagonal display orientations might lie in the use of one of the alternative reference systems mentioned above. These targets are so close to either a horizontal or a vertical alignment with one landmark that the use of these reference systems might be very helpful. Participants might thus adopt a strategy of switching reference systems if it allows them to encode the spatial relations more efficiently or more accurately. It would be interesting to test, for example, if a similar effect would occur in situations where the landmark configuration might change between the first and the second presentation (e.g., from horizontal to diagonal). In this case, reference systems other than the two landmarks would be of only little use in situations where the configuration changed.

Most importantly, however, the results show that even such a simple pattern of landmarks as the one used in this experiment suffices to establish an allocentric spatial organization that influences the memory of spatial location. The results do not tell us, however, at which point of processing the allocentric reference system induced by the landmarks is established and used to encode the necessary spatial relations. Like most studies using the distortions of spatial locations as a means to identify the dominant reference system, the time it takes to reproduce a location limits the temporal sensitivity of the measure. Other methods, such as the priming paradigm employed by Carlson-Radvansky and Jiang (1998), can identify effects of reference systems at a much higher temporal resolution. While the results of Experiment 1 show that a few seconds, consisting of retention interval and spatial reproduction time, are sufficient to produce spatial distortions, it would be interesting to trace the role of the landmark-based reference system over brief periods of time.

The solution to this problem lies in using a visual discrimination task to investigate spatial memory distortions (Freyd & Johnson, 1987; Werner & Diedrichsen, submitted). In this case, the observer does not have to physically reproduce a spatial location, but merely judge whether the location of a target has changed between two presentations. This allows for a tight control of presentation times and very short retention intervals. As Werner and Diedrichsen were able to show, spatial distortions due to a landmark-based, allocentric reference system were observable at retention intervals of only 50 ms, suggesting that allocentric coding is already used at early stages of spatial processing. The following experiment employs a similar strategy to probe the time course of allocentric spatial coding.

## 3 Experiment 2

The purpose of this experiment was to investigate the time course of the distortion effect in the two-landmarks task by using a visual discrimination paradigm. Instead of asking participants to reproduce a target location, they now had to tell whether a target had been displaced to the left or to the right during the masking interval. In addition to the 400-ms mask used in experiment 1, we used a 100-ms mask to see whether distortion effects were already present at this early stage.

Unlike the method employed by Werner and Diedrichsen (submitted), where the participants had to judge whether or not a dot had moved between two presentations, the participants' task in this experiment was to report the *direction* of target displacement rather than to simply detect its presence. This allowed us to sample psychometric functions that could be readily analysed by statistical standard procedures, yielding estimates for the bias and the sensitivity of individual participants.

More specifically, assume that a target is in a region of the display where the landmark induces a *rightward* bias in the memory representation of the target. Now consider that the target is physically displaced to the right during the masking interval. Because the memory representation has also drifted to the right, the apparent displacement should be small, and the likelihood of participants reporting a rightward displacement should also be small. Compare this with the situation in another region of the display where a *leftward* bias of the memory representation is induced. If the target is still physically displaced to the right, the apparent displacement should appear large, and the likelihood of reporting a rightward displacement should be large, too.

### 3.1 Method

*Participants.* Six undergraduate students (age 22 to 29, all female, two of them left-handed) of the Institute of Psychology at the University of Göttingen participated for course credits or for a payment of 12,- DM per hour. Their vision was normal or corrected-to-normal.

*Apparatus.* The setup was the same as in experiment 1, only that the viewing distance was 80 cm.

*Stimuli.* To allow for direct comparisons between experiments, stimuli were the same as in experiment 1, with the following exceptions. We used only one stimulus orientation, so that the two landmarks were always horizontally aligned. The landmarks were filled in this experiment. There were only five target positions: one at the center of the screen, the other four positions at y-coordinates of ±15 px (±.54°) and x-coordinates of ±30 px (±1.07°). These targets corresponded to the five innermost target positions from Experiment 1. They were chosen because they had shown strong distortions along the x coordinate in experiment 1, and this distortion had been independent of display orientation. Furthermore, they were all near the center of the display which reduces possible effects of stimulus eccentricity when fixating on the center.

*Procedure.* A trial began with the presentation of the two landmarks within the white rectangular frame as in Experiment 1 (Fig. 4). After 500 ms, the target appeared at one of the five possible locations and remained on the screen for 500 ms before it was replaced by a 320 x 200 px dynamic mask for either 100 or 400 ms. Immediately following mask presentation, the target was presented again, but this time with a displacement of 0, 1, 2, or 3 px to the left or right of its original position. Participants were not informed that in some cases no displacement occured. The landmarks remained visible until the participant responded and were also visible during the masking interval. The participants' task was to indicate whether the target had been displaced to the left or right by pressing the appropriate key ("4" for "left", "6" for "right" on the numerical pad of the computer keyboard) with the index or ring finger of their right hand, respectively. The instruction emphasized accuracy rather than speed and encouraged participants to guess when they were not sure about the direction of target displacement. The keypress response elicited a 2000 Hz, 100 ms tone, and a warning tone (100 Hz, 500 ms) was sounded when a key other than the two permitted was used. After an intertrial interval of 500 ms, the next trial began. Throughout the experiment, no feedback concerning the level of performance was given.

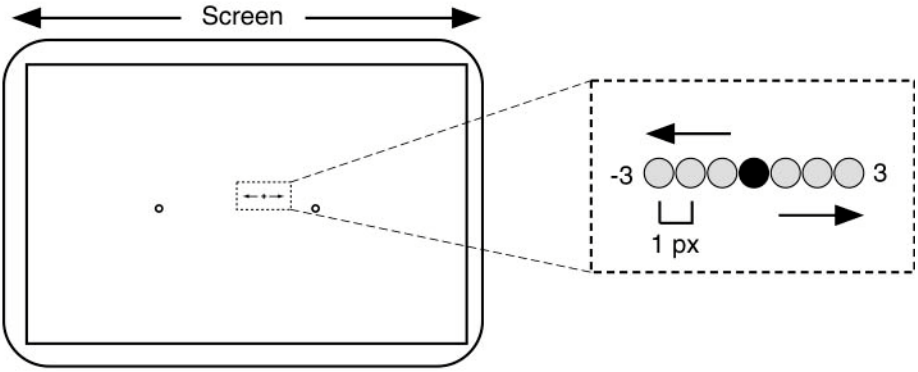

**Fig. 4.** Display configuration in experiment 2. Stimuli were presented bright against a dark background. The panel on the right represents an enlarged section of the display, showing schematically the 7 possible target displacements for one target position

Stimulus conditions were counterbalanced such that each combination of target position, mask duration, and target displacement occured randomly and equiprobably, with each combination appearing once every two blocks. The center target position appeared twice as often as any other target position to yield equal numbers of observations for x and y coordinates.

Each participant took part in four sessions of 16 blocks with 42 trials each, resulting in a total of 2,688 trials. Each session started with an additional practice block of 42 trials. At the beginning of the first session, participants trained the discrimination task in a short demonstration program using larger target displacements. After the last session, they were debriefed and received an explanation of the purpose of the experiment.

### 3.2 Results

For the following analyses, response times shorter than 100 ms and longer than 999 ms were excluded (0.92 %). Additionally, we excluded all trials where a participants' response times were more than three standard deviations above or below her average response time (2.37 %). Practice blocks were not analysed.

Results are shown in Figure 5. Psychometric functions were analysed by multiple logistic regression (Agresti, 1996). We used a Wald statistic, reported here as *W*(*df*), where *df* denotes the degrees of freedom. The regression model contained the Target Displacement, Target Position, and Mask Duration main effects, the Displacement x Mask Duration interaction, and the Position x Mask Duration interaction. Model fit was excellent[1], with a high correlation of the observed and predicted means, $r = .996$.

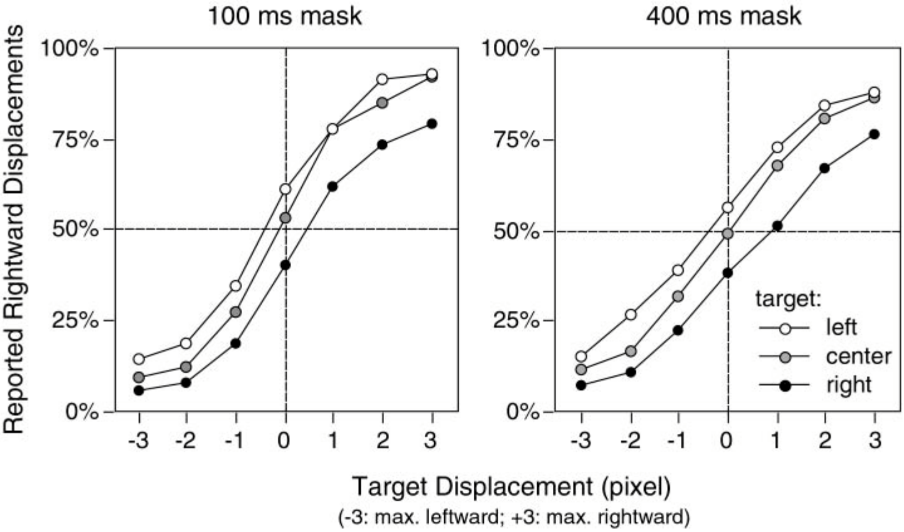

**Fig. 5.** Psychometric functions from experiment 2, separately for the two masking intervals. Spatial memory distortions in one direction lead to an increase of displacement judgements in the opposite direction (see text)

Not surprisingly, there was a main effect of Target Displacements, indicating that participants were able to discriminate leftward and rightward displacements, $W(1) = 3907.66$, $p < .001$. Importantly, there was a clear effect of Target Position in the predicted direction, $W(2) = 352.78$, $p < .001$, indicating that compared with targets at the midpoint between the two landmarks, participants were more likely to report a rightward displacement for targets on the left, $W(1) = 40.82$, $p \leq .001$, and a leftward displacement for targets on the right, $W(1) = 153.06$, $p < .001$.

There was a small main effect of Mask Duration, reflecting a tendency to report leftward rather than rightward displaments, which was more pronounced at the longer mask duration, $W(1) = 5.92$, $p < .050$. More importantly, psychometric functions were steeper at the shorter masking interval (i.e., a Displacement x Mask Duration interaction), indicating a loss of sensitivity with increasing mask duration, $W(1) = 50.13$,

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[1] The same model was used for the data of individual participants, also with excellent fit, $.967 \leq r \leq .996$.

$p < .001$. There was no evidence of a Position x Mask Duration interaction, suggesting that the distortion effect did not vary with mask duration, $W(2) = .92$, $p = .632$.

Participants differed widely in sensitivity and overall response bias. The predicted distortion effect occured in four out of six participants, causing responses to be biased towards the side opposite to the target position, $46.77 \leq W(2) \leq 186.14$, all $p < .001$. One participant, however, showed the reverse effect, $W(2) = 18.76$, $p = .001$.

A significant increase of distortion with increasing masking interval occured in only one participant, $W(2) = 22.63$, $p < .001$. In two other participants, however, the distortion effect *decreased* with increasing mask duration, $W(2) = 23.98$, $p < .001$, and $W(2) = 10.25$, $p = .006$, respectively. In the remaining participants, this effect was not significant, $2.37 \leq W(2) \leq 6.79$, $.034 \leq p \leq .306$.

### 3.3 Discussion

Experiment 2 examined the distortions in spatial memory observed for the five innermost target positions in Experiment 1 in more detail. The results are consistent with the assumption that memory representations are biased away from the midpoint between the two landmarks, thereby increasing the probability of reporting a physical target displacement in the opposite direction. Judgements for targets presented directly at the midpoint, however, remain essentially undistorted.

The significant bias in judgments with the short masking interval indicates that even for very brief retention intervals of only 100 ms the landmark-based, allocentric reference system affects the memory for spatial locations. This finding replicates the results of Werner and Diedrichsen (submitted) who found evidence for spatial memory distortions after only 50 ms. However, in the experiments reported here there was no effect of mask duration on the size of the distortion. Unlike previous findings, the distortion seems to be as strong after 100 ms as after a 400 ms retention interval. This suggests that spatial memory distortions can be fully developed after only 100 ms, which is much shorter than the asymptotic 400 ms reported by Werner and Diedrichsen (submitted). It thus seems clear from the results that spatial memory distortions can develop over brief time spans, suggesting that memory representations are involved quite early in the course of visual processing.

As expected, the sensitivity for target displacements diminishes for the longer masking interval. This does not, however, coincide with an increase in spatial distortions, indicating a dissociation between the size of a distortion and an observer's sensitivity.

## 4 Conclusion

The goal of this paper was to introduce the analysis of spatial distortions as a useful tool to identify the role of different spatial reference systems in human memory. In the first experiment, systematic biases were found for observers' reproductions of dot locations in a simple two-landmarks situation. When changing the orientation of the two landmarks, the distortion pattern followed the new orientation, establishing the dependence of the distortion on the allocentric reference system induced by the landmarks. The distortion pattern of remembered locations thus can identify the dominant spatial reference system used to encode location information within a particular task (see also Huttenlocher, Hedges, & Duncan, 1991; Nelson & Chaiklin, 1980).

By changing the experimental procedure in the second experiment, we were able to demonstrate the presence of spatial memory distortions even for very brief retention intervals of 100 ms. Although this does not necessarily imply that the spatial memory distortion has fully developed 100 ms after the offset of the stimulus, it clearly marks an upper limit for the relative processing lag that is needed between two stimuli, so that one is already showing the biasing effect of the allocentric reference system, while the other is not yet affected by it. Moreover, the results have strong implications for the comparison process between the two mental representations involved, the representations of the remembered and the presented location. One explanation could be that the biasing effect of the allocentric reference system develops gradually as soon as the visual representation of a stimulus starts to decay, so that a comparison process has to match a biased memory representation with a yet undistorted visual representation of a stimulus (also compare Werner & Diedrichsen, submitted). Simulations of early visual cortical areas suggest that topographic representations of spatially extended stimuli decay in a gradual fashion, with interactions between stimulus representations leading to nonhomogenous rates of decay across the visual field (Francis, 1997; Francis & Grossberg, 1994). Because the distortion effects described here arise quite early in visual processing, one might speculate whether a landmark-induced allocentric reference system could lead to spatial distortions in topographically organized visual areas such as V1 to V5.

By using a combination of spatial reproduction and spatial discrimination tasks, as demonstrated in this paper, the role of different reference systems can be investigated at a high spatial and temporal resolution (Werner & Diedrichsen, submitted), allowing researchers to investigate the time course of spatial reference systems at a behavioral and neuropsychological level. The exact description of spatial distortion allows more than just a classification of the general type of reference system used to encode a location (e.g., allocentric vs. egocentric). It additionally can shed light on the particular way space is structured by a reference system. Eventually, it might even lead to general theories of how spatial and geometrical relations are perceived and encoded (e.g., Huttenlocher et al., 1991). This might help to identify the computational dynamics and brain structures associated with particular reference systems.

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