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Separate simultaneous processing of egocentric and relative positions

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Abstract

It is well established that all kinds of visual attributes are processed separately within the brain. This separation is related to differences in the information that is relevant for the different attributes. When attributes differ greatly (such as colour and motion) it is obvious that they must rely on different information. However, separating the processing of different attributes could also allow highly related attributes to evolve independently, so that they end up being judged on the basis of different types of information. Here, we examine the case of egocentric and relative localisation. For judging egocentric positions, the orientation of the eyes has to be taken into account. This is not so for judging relative positions. We demonstrate that these two attributes can be processed separately by showing that simultaneous judgements of relative and egocentric position differ in their dependency on eye orientation. Subjects pursued a moving dot. We flashed either single targets, or pairs of targets with a 67 ms interval between them, directly below the subjects' gaze. As the eyes were moving during the 67 ms interval, the retinal separation between pairs of targets was different from their actual separation. Subjects indicated the position at which they saw the targets with reasonable reproducibility, with a consistent bias in the direction of the eye movement. However, when two targets were flashed, the indicated separation between them usually coincided with their retinal separation, rather than with their actual separation. We conclude that egocentric and relative spatial positions can be estimated separately and simultaneously, on the basis of different types of information. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Many aspects of objects in our surrounding can be established visually: surface properties such as colour and texture, intrinsic spatial properties such as shape and size, extrinsic spatial properties such as position and motion, and so on. The information that determines certain attributes is completely different from that which determines others. For instance, there is no relation between an object's colour and its motion; two attributes that are known to be processed separately within the brain (Livingstone & Hubel, 1988; Zeki & Shipp, 1988). An advantage of separating processing of such different attributes is that each can evolve separately, so that they can come to be based solely on the most suitable sources of information. This limits the scope of inputs that are considered for each attribute, and therefore simplifies the processing involved.

The hypothesis that processing evolves largely independently for each attribute predicts that there could also be major differences between the information that is used for determining strongly related attributes. A consequence of separate processing of related attributes is that perceived properties need not be consistent with one another (Brenner & van Damme, 1999). For instance, objects can appear to move faster (Brenner, van

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den Berg & van Damme, 1996) or further (Abrams & Landgraf, 1990) than one would predict from the perceived change in position, or to be longer than one would predict from the perceived positions of their ends (Mack, Heuer, Villardi & Chambers, 1985). We here examine egocentric and relative localisation. Egocentric and relative positions are so closely related that it is not even evident that they could be separate attributes. However, we predict that they should be, because there are clear advantages of processing them independently.

Egocentric localisation is essential for manipulating objects. For instance, in order to reach out for an object we have to track where it is relative to ourselves. This is necessary to ensure that we move our hand in the appropriate direction. To obtain such egocentric information it is not enough to consider the retinal position of the object's image. The orientation of the eyes also has to be taken into account.

For many other tasks, it is enough to know the relative positions of structures of interest. Such information may help establish permanent relationships (e.g. shapes). Knowing a target's position relative to the simultaneously visible hand could even help guide the hand just before contact. Relative positions could be judged by combining egocentric positions. Since the same eye orientation signal presumably contributes to all egocentric positions, misjudging the eye orientation will influence the positions of all simultaneously visible structures in the same way, so that relative positions could be judged much more accurately than are the individual egocentric positions. Alternatively, however, relative retinal positions could be used directly. This is a fundamentally different mechanism, because in this case the retinal separations are determined before eye orientations are considered, and the latter only serve to help interpret these separations (e.g. to convert them to actual distances in space; Brenner & van Damme, 1999).

For simultaneously visible structures both mechanisms predict the same performance: more accurate relative positions than egocentric positions. However, if the structures are not visible simultaneously, and eye orientation changes between presentations, the hypothesis that egocentric positions are combined predicts correct average performance (though more variable because the eye orientation signal is no longer the same for both structures), whereas the hypothesis that relative retinal positions are used predicts dramatic systematic errors.

In the present study we examine whether relative positions are determined independently of the perceived egocentric positions. We do so by presenting targets sequentially while the subjects pursue a moving dot with their eyes. We find that subjects indicate the position at which they saw a target with reasonable reproducibility, with a consistent bias in the direction of the eye movement. When two targets are presented briefly after one another, the perceived separation between them usually coincides with their retinal separation, rather than their actual separation.

2. Materials and methods

Subjects sat with their chin on a chin rest, 57 cm from a large screen (38.0 × 28.5 cm; 640 × 480 pixels; 120 Hz). The background on the screen was grey (25 cd/m^2) with a faint random texture (10% lighter and darker grey dots). The room was dark except for indirect illumination by the image on the screen. Eye movements were recorded with an SMI EyeLink Gazetracker (SensoMotoric Instruments GmbH, Teltow, Germany). Stimuli were produced using some of the software routines from the 'VideoToolbox' (Pelli, 1997).

2.1. The stimuli

The subjects were instructed to pursue a yellow dot (0.25° diameter; 69 cd/m^2) as it moved rightward at a velocity of 13 deg/s across the screen. This dot always started 15° to the left of the centre of the screen. After between 750 and 1250 ms of pursuit, a target was visible during one frame. This target was either a 2.25° long, 0.12° wide vertical white (75 cd/m^2) line, or a 0.12° wide, 0.75° diameter white ring. On some trials, a second target, always of the other kind, was presented 67 ms (eight frames) later. The targets were always presented exactly below the subjects' gaze. The centre of the target was 1.5° below the dot, but aligned horizontally with the eye rather than with the dot. Thus, the targets were presented at well-defined positions on the retina, but their positions on the screen depended on the gain of pursuit during that trial. Eye movements were recorded at 250 Hz. The delay between sampling an eye movement and this information being incorporated in the image was about 20 ms. This delay was not considered when presenting the targets, so the latter were always presented about quarter of a degree to the left of the momentary direction of gaze. The high contrast and considerable size of the targets made them very easy to see at the eccentricities at which they were presented (despite the short duration).

There were eight conditions. Two with single targets: either a line or a circle. Two in which the two targets were superimposed on the retina: either the line or the circle was presented first. Two in which the second target was presented 0.346° to the right of where it would have to be presented for the two to be superimposed on the retina: again with either target first. And two in which the second target was presented 0.346° to the left of that position.

2.2. The settings

After each stimulus presentation subjects were required to make their settings. They did so by moving the computer's mouse. If a single target was presented, the same target appeared at a random horizontal position and the same height as the original target. The target was now continuously visible, and moving the mouse horizontally moved it laterally across the screen. Subjects had to indicate where the original target had been presented by moving the new target to that position and pressing the button on the mouse to indicate that they had done so. If two targets had been presented, subjects first had to set the circle in the manner just described, and then to do the same for the line.

2.3. Procedure

Each session started with a nine-point calibration of the eye movement recordings. After calibration the various conditions were presented in random order. Subjects never knew whether a second target would be presented. The single targets were each presented 20 times, giving a total of 40 presentations per subject. The double targets were presented five times for each retinal offset and order in which the two targets were presented, giving a total of 30 presentations per subject. Eye movements were recorded for later analysis. Half way through the session, the calibration was validated.

2.4. Eye movements

During post-hoc analysis of the eye movement traces, all trials were discarded in which saccades were made between 100 ms before the first target was presented, and 100 ms after the last one was presented. Fig. 1 shows an example of a trial that was considered adequate (A, good pursuit) and one that was not (B, rejected). Only the settings from the former kind of trials were used in the further analysis of the results. Table 1 shows the percentage of trials on which there were no saccades close to the time of stimulus presentation, as well as the gain of ocular pursuit during the approved trials.

3. Results

On some trials, a single circle or a line was flashed at an unpredictable moment directly below the subject's

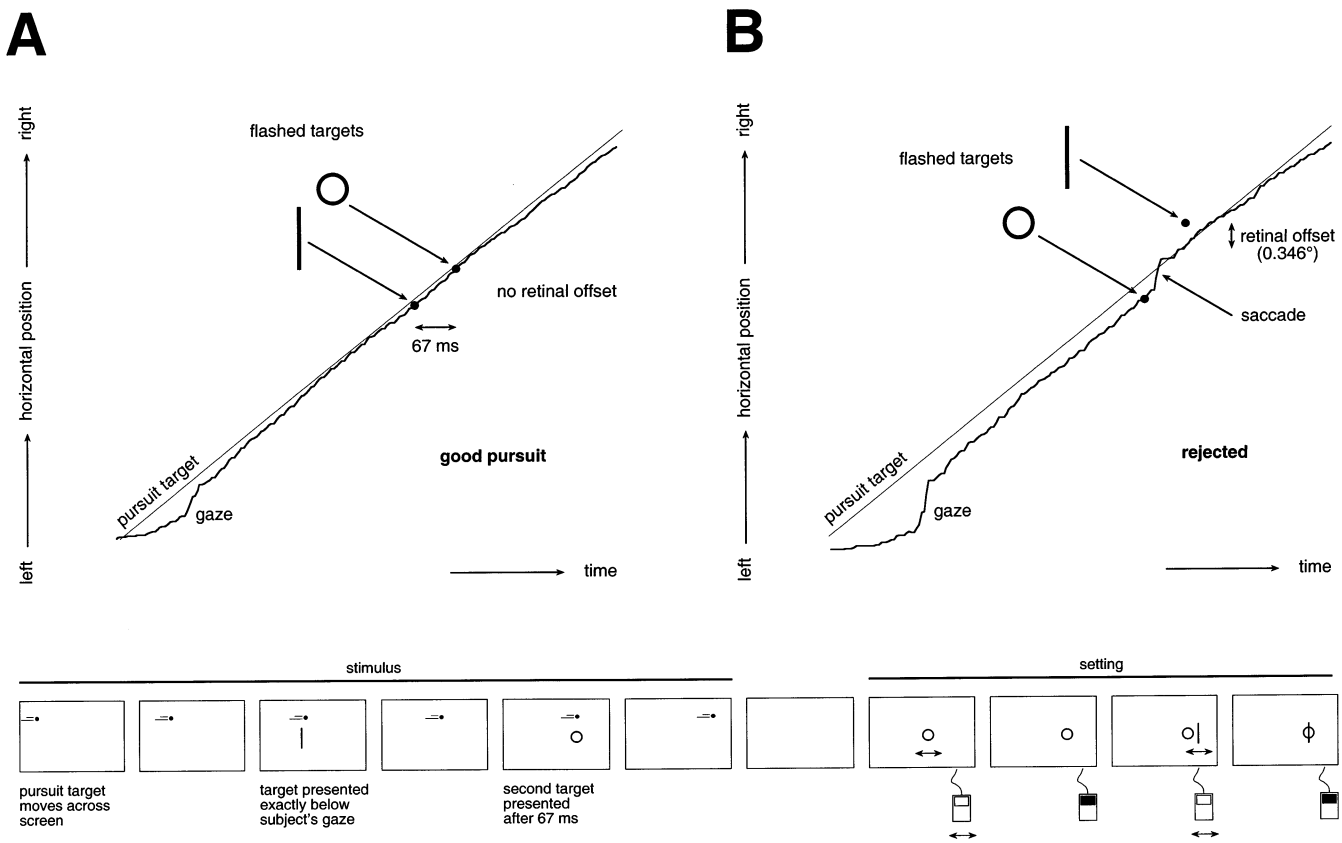

Fig. 1. Schematic representation of the methods. Top: examples of a trial with good pursuit (A) and one with a saccade too close to the moment a target was presented (B). In the latter case the second target was displayed 0.346° to the right of where the subject was looking. The dot that was to be pursued always moved at 13 deg/s. Bottom: schematic representation of the sequence of events during a trial with two targets.

Table 1
Several experimental values for the individual subjects

Subject	AB	EB	EH	FC	JH	MT	MV	TC	WB
% Trials approved	80	94	63	80	66	44	69	81	66
Pursuit gain[a]	1.00	1.00	0.97	1.08	1.06	0.96	1.06	0.87	0.96
SD set position[b] single targets (°)	1.13	0.80	1.29	0.86	1.49	1.48	1.25	1.04	1.09
SD real distance[c,d] between targets (°)	0.10	0.09	0.20	0.08	0.07	0.05	0.16	0.19	0.11
SD set distance[c] between targets (°)	0.40	0.17	**1.35**	0.12	0.25	0.15	**1.89**	0.31	0.15

[a] Mean value during the 67 ms after the (first) stimulus; approved trials only.
[b] Measured relative to the real position.
[c] Mean of the standard deviations for the distance between the circle and the line for the three offsets (none; ±0.346).
[d] The distance varies between trials as a consequence of differences in pursuit gain.

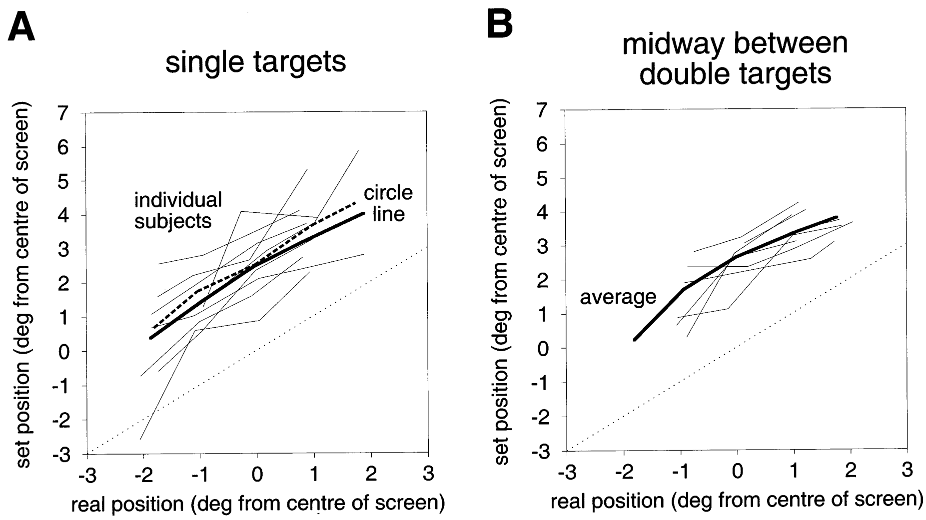

Fig. 2. Indicating the perceived position on the screen. Settings were pooled into 1° bins of real position, and the average real and set position was calculated for each bin. Only values based on at least three settings are shown. Positive is to the right (in the direction of pursuit). The thin dotted line shows what subjects should have set to obtain a perfect match. (A) Set positions for trials with single targets. Thin lines: data for individual subjects averaged across targets. Thick lines: data for each target averaged across subjects. (B) Set positions for trials with two targets. The positions are the averages of the two targets. Thin lines: data for individual subjects. Thick line: average across subjects.

gaze. After the trial subjects were asked to place an identical figure at the position at which the target had been flashed. Fig. 2A shows the mean set position as a function of the real position of such targets. Data are presented for individual subjects (averaged over targets; thin lines) as well as for each kind of target (averaged over subjects; thick lines). Subjects consistently perceived the target to be slightly further in the direction of the eye movement than it really was. The extent to which they did so differed between subjects.

On the rest of the trials two targets were flashed, with an interval of 67 ms between the flashes. The first target was identical to the single targets mentioned above. The second target was either also flashed directly below the subject's gaze, thus 0.87° to the right of the first target (if pursuit was perfect), or 0.346° further to the left or right of this. Fig. 3 shows the set distance between the two targets as a function of the real distance between them. The black diagonal line indicates veridical performance. The thick grey line represents the settings one would expect if subjects relied exclusively on retinal information and pursued the dot perfectly. Most subjects (circles) perceived the positions of the targets relative to each other in accordance with their retinal separation. This was clearly not the result of some kind of compression of perceived space (Morrone, Ross & Burr, 1997), because the retinal separations were fully accounted for (open circles). Two subjects, however, appeared to be doing something completely different (triangles). An examination of the variability in their settings (Table 1) may give us a clue as to what they were doing.

All the other subjects (the ones who judged relative position on the basis of retinal separation) exhibited much less variability (expressed as the standard deviation: SD) in their judgements of relative position than in their judgements of the egocentric position of single targets. Thus their judgements of relative position could not have been based on comparing independent estimates of the positions of the two targets. (Doing so would have resulted in a standard deviation that is about 1.4 times as large as that of each on its own unless the eye orientation signals at the two moments are not independent. We will see in the next paragraph that they probably are independent. The standard deviation could be even larger, because controlling the *retinal* stimulation introduces variability in the real distance between targets due to variability in pursuit gain; see Table 1).

The two subjects (EH and MV) who did not set the relative positions in accordance with the retinal separation were very much more variable in their settings of relative positions. In fact, their standard deviations were close to what we would predict if they were making two independent judgements, each in the manner that their judgements were made when only one target was present. If this interpretation is correct, then the eye orientation signals must be more or less independent at the two moments. These subjects presumably considered the two targets as independent structures, and made two separate egocentric judgements (in accordance with the task).

Fig. 2B shows the average of the set positions of the two targets as a function of the average of their real positions, in the same manner as was done for single targets in the left panel. Since there were fewer trials with two targets, and the time during which subjects were not to make saccades was longer, fewer points contribute to this figure. However, it is evident that

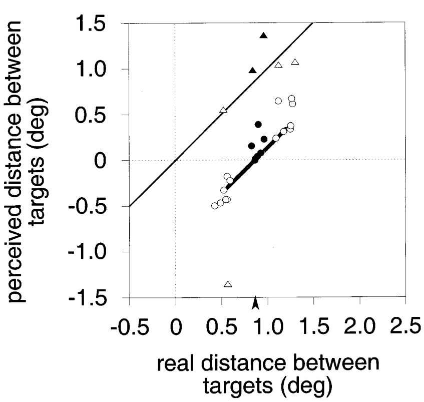

Fig. 3. Set distance between targets for trials with two targets. Thin black diagonal line: expected settings if the distance between the targets was perceived veridically. Thick grey line segment: expected settings if based exclusively on the retinal image (assuming perfect pursuit, open symbols would lie at the ends and solid symbols at the centre of this line). Arrow: real distance that the eye would cover in 67 ms if pursuit of the target moving at 13 deg/s were perfect. Solid symbols: both targets presented directly below the subject's gaze. If pursuit were perfect the real distance between them would be the value indicated by the arrow. Open symbols: second target presented 0.346° to the left or right of where the subject is looking. Circles: data for the subjects who set the relative positions much more reliably (smaller SD; see Table 1) than the egocentric positions of single targets. Triangles: data for the two subjects who did not (EH and MV; see Table 1).

subjects were placing the combination of line and circle in approximately the same manner as they had been placing the individual components. These settings were not more variable. The average (across subjects) of the standard deviations of the set positions (with respect to the real position) was 1.03°, compared with 1.16° for single targets (see Table 1). Since subjects always first set the circle one may expect the settings for the line to be more variable. This was not so. When considered independently, the average standard deviation was 0.99° for the circle and 0.98° for the line (similar to the values when the stimuli were presented alone).

4. Discussion

It was well known that subjects can localise targets quite accurately during smooth pursuit (Hansen, 1979). Nevertheless, when Stoper (1967); as cited in Matin, 1986, p. 39) flashed targets while subjects were pursuing an unrelated structure, he found that eye orientation was not taken into consideration for determining relative positions of successively presented targets unless the targets were separated in time by more than 700 ms. The tendency to misperceive targets in the direction of the eye movement has also often been reported (Mita, Hironaka & Koike, 1950; Mitrani, Dimitrov, Yakimoff & Mateeff, 1979; Mateeff, Yakimoff & Dimitrov, 1981; Brenner & Smeets, 1998). Thus, none of the findings is new. However, we demonstrate both phenomena within single presentations. This is not trivial, because all sorts of methodological differences between studies are known to influence whether eye orientation is considered.

Rock and Linnett (1993) found that subjects *did* consider eye orientation when combining lines that were presented at intervals of 250–400 ms to form a shape. They found that subjects no longer accounted for eye orientation on the basis of an extra-retinal signal if there was a visual reference. In that case subjects' judgements were based on the positions of the flashed targets relative to the visual reference, even when the reference was actually moving. In our study we had ample stable visible structures that could have served as a reference. If subjects had judged the targets' positions relative to these structures they would have perceived the relative distances as presented on the screen, which they did not. They may, however, have judged the flashed targets' positions relative to the moving dot, rather than relative to each other.

To find out whether this was what subjects were doing we had four subjects repeat the two-target part of the experiment with three conditions (30 trials per condition, divided into 6 sets on the basis of the order of appearance of the targets — target or circle first — and the retinal distance between the first and second

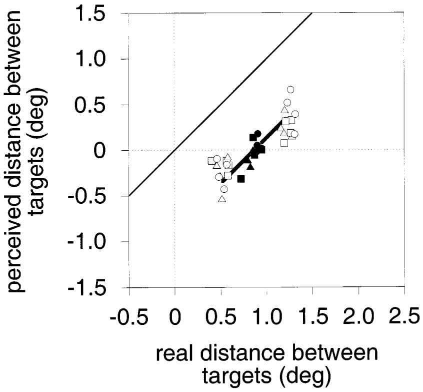

Fig. 4. Influence of removing the moving dot (the target of pursuit) near stimulus presentation. Format as in Fig. 3. Circles: moving dot constantly visible Triangles: moving dot disappeared for 133 ms. Squares: moving dot disappeared for 267 ms. Data of four subjects (EB, FC, MT, TC).

target). The first condition was identical to the original one with two targets. The second was the same except that the moving dot disappeared when the first target flashed, and only reappeared 67 ms after the second flash. In the third condition the moving dot disappeared 67 ms before the first target flashed and only reappeared 133 ms after the second one did. The average set position was 2.9° to the right of the flashed targets when the moving dot did not disappear, 2.5° to the right when it disappeared for 133 ms, and 2.3° when it disappeared for 267 ms. Fig. 4 shows the set distance between the targets as a function of the real distance in the same format as Fig. 3. It is evident that the simultaneous presence of the moving dot is not critical.

These results support our notion that subjects judge the relative positions of the two flashed targets from their retinal separation. However, our conclusion would not have been very different if we had found that subjects used the moving dot as a reference, because in either case they ignore the change in eye orientation during the 67 ms between the targets. For the localisation of the targets in space, on the other hand, the persistent bias in the direction of the eye movement confirms that we are dealing with egocentric judgements that consider eye orientation (but do so incorrectly).

Whether subjects report egocentric positions or relative positions appears to differ between studies, between aspects of the task, and even between subjects. In the present study two subjects seemed to perceive the two targets as separate structures, whereas the rest appeared to perceive a single structure whose shape was based on the targets' relative retinal positions. Similarly, Hayhoe, Lachter and Feldman (1991) found that some subjects needed a visible reference to reliably judge the relative positions of targets presented across saccades, whereas others did not. Presumably some subjects are more disposed to considering asynchronously presented parts as separate entities. We are not claiming that subjects are unable to combine egocentric positions to judge relative ones. Our claim is that they can determine relative positions directly on the basis of different information. This dichotomy is consistent with the suggestion that eye orientation is only considered at the moment that egocentric localisation is explicitly required (Henriques, Klier, Smith, Lowy & Crawford, 1998).

5. Conclusions

We conclude that egocentric and relative spatial positions can be estimated independently, on the basis of different types of information. Eye orientation is only considered when evaluating egocentric positions. Thus our results provide support for the notion that even judgements of highly related visual attributes can be based on more or less independent processing (Mack et al., 1985; Abrams & Landgraf, 1990; Brenner & van Damme, 1999). The advantage of doing so lies in the ability to limit the information that is considered for each judgement to the information that has proven to be the most suitable.

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