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Judging an Object's Velocity when its Distance Changes Due to Ego-Motion

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This paper examines how one accounts for ones own movements when judging the velocity of a moving object, with emphasis on ego-motion perpendicular to the direction in which the object is moving. The "object" was a square that was tracked with smooth pursuit eye movements as it moved horizontally across a computer screen. Half-way through the presentation, the image on the screen changed in a manner simulating ego-motion in depth. At the same time, the speed with which the square moved across the screen also changed. Subjects were asked to report whether the target moved faster, at the same speed, or more slowly after the simulated ego-motion. The change in target velocity that was required for it to appear to continue to move at the same speed was determined for simulations containing different aspects of the information that is normally at our disposal. The results show that the change in the size of the image of the target, the expansion or contraction of the image of the surrounding, and differences in target motion between the two eyes (giving rise to vergence eye movements), all contribute to rendering the perceived object velocity independent of ego-motion.

Motion perception   Optic flow   Stereopsis   Eye movements   Velocity

An intriguing problem for studies on perceived object motion is how we prevent our own movements from interfering with judgements of the motion of the object in question. Both ego-motion and object motion can displace the image of the object on the retina. Moreover, they can cancel each other; as happens when we try to prevent the image of an object from moving across the retina by tracking the object with pursuit eye movements.

In a previous study (Brenner, 1991a), subjects watched a target move horizontally through an empty room (shown in perspective on a computer screen). At a certain point during the presentation, the room's image on the screen could change in a manner simulating ego-motion (or texture moving across the far wall). Subjects were asked to compare the target's initial velocity, with that during the simulated ego-motion. A floor of tiles made it possible to differentiate between simulations of (1) rotation of the observer, (2) translation of the observer parallel to the target's trajectory and (3) texture moving across the far wall. Surprisingly, there was no difference between the three conditions: the perceived target velocity depended almost exclusively on the target's motion relative to the (texture on the) far wall.

Basing velocity judgements on target motion relative to the most distant surface is adequate for accounting for ego-rotation. For ego-translation parallel to the target's trajectory, judgement errors should occur if the target is nearer than the background. One might therefore expect that specifying that the target is considerably nearer than the background would influence the perceived velocity. However, varying the simulated target distance, by changing target vergence and relative disparity, did not influence subjects' velocity judgements. A possible explanation for simply relying on relative motion, is that we usually look in the direction in which we are moving, rather than sideways, especially if ego-motion is fast enough to cause significant motion parallax.

An explanation for the finding that velocity judgements were even based on relative motion during simulated motion of the texture on the far wall, is that subjects interpreted the wall as being a window, which moved together with them—and the floor of tiles—relative to the static background—and the target—"outside" (Johansson, 1977). If so, this condition should also be considered as simulated ego-translation parallel to the target's trajectory.

In the present study, I examine the influence of simulated ego-motion perpendicular to the target's trajectory (approximately in the direction in which we are looking). Ego-motion in depth changes the distance between the observer and the trajectory of the target and thereby also the relationship between the target's actual velocity (relative to the environment) and its angular velocity (relative to the observer). The question is, how the changing angular velocity and information on the changing distance, are combined when judging the target's actual velocity.

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OPTIC FLOW

When the observer moves towards the target, its image on the retina grows. When the observer moves away, it shrinks. The size of the target's retinal image is approximately inversely proportional to its distance. The target's angular velocity with respect to the eye (retinal velocity if no eye movements are made; velocity of ocular rotation if the target is pursued perfectly) is also inversely proportional to its distance. When ego-motion changes the distance between the observer and the target, therefore, retinal size and angular velocity change in a similar manner. Scaling angular velocity by retinal target size could therefore prevent ego-motion in depth from affecting the perceived velocity. If the target is not spherical, additional changes in image size can be caused by changes in the orientation of the target relative to the observer. For accurate velocity judgements based on retinal image size, therefore, changes in orientation must be accounted for on the basis of deformations of the image of the target (Koenderink, 1986). We have some experimental evidence that changes in orientation are indeed accounted for (Brenner & Monen, 1992).

The influence of target size on perceived velocity has been reported to be quite limited (Brown, 1931; Raymond, 1988). However, when the velocities of two targets, at different locations, are compared by looking at them successively, as done in previous studies, there is no explicit reason to assume that the two targets are actually the same size (and thus at different distances). In the present study, subjects compare the velocity of a single moving target during successive time intervals. The target moves for some time at an initial velocity, gradually changes its size and velocity and then continues moving for some time at the final velocity (although the target is sometimes not visible while its velocity changes, it always continues to move along the same path).

The changes in the size of the target's image (on the screen or retina) could nevertheless still be interpreted as an actual change in target size, rather than as a change in its distance. Moreover, changes in distance could either be the result of motion of the observer, or of additional motion of the target towards the observer. If there are visible structures in the background, these structures will only expand or contract if ego-motion is the cause of the changes in target size (Gibson, 1979). Whether such analysis of the global optic flow contributes to judgements of object velocity is examined by comparing simulations with and without a structured background.

BINOCULAR STEREOPSIS

Target size is not the only parameter that changes with the distance of the target. An obvious alternative source of information on changes in the distance of the target is binocular stereopsis (Rock, Hill & Fineman, 1968; Epstein, 1978). As the observer approaches the target, or moves away from it, the image of the target will shift in slightly different ways in the two eyes (changes in retinal disparity), in accordance with changes in the target's position with respect to each eye. The subject will normally respond by making vergence eye movements to keep both eyes oriented towards the target, which in turn will shift the background across the retina.

Erkelens and Collewijn (1985) have shown that the percept of motion in depth depends on differences between the relative displacements of images of surfaces—that are at different distances from the observer—in the two eyes (changes in relative disparity), rather than on changes in the orientation of the eyes (ocular vergence). Relative disparity is (almost) independent of the orientation of the eyes. However, relative disparity depends on the relative distances of surfaces. As ego-motion changes the distance to the background, as well as to the target, changes in relative disparity are not directly related to changes in the distance of the target (unless the background is much further away than the target, so that changes in the distance to the background can be ignored).

An alternative is to rely on target vergence. Changes in target vergence give rise to different retinal displacements of the target's image in the two eyes, until this is counteracted by tracking the motion in depth with vergence eye movements. However, whereas the difference between angular velocity before and after ego-motion in depth only depends on the proportion of the distance to the target that is traversed; changes in target vergence are different, for the same proportion of distance traversed, at different actual target distances. The difference between the retinal slip of the target's image in the two eyes (before compensatory vergence eye movements are made) is, therefore, not directly suitable for accounting for changes in the distance of the target. However, the signals that are responsible for the vergence eye movements that maintain fixation on the target may be represented in a manner related to external space, rather than to angles of rotation. The actual target distance could thus be accounted for on the basis of the orientations of the eyes (and possibly their state of accommodation). Eye movements induced by visual signals can indeed depend on the eyes' orientations (and their state of accommodation; Busettini, Miles & Schwarz, 1991). Moreover, although ocular vergence alone does not result in perceived motion in depth, it does result in changes in perceived size (Regan, Erkelens & Collewijn, 1986). It does, therefore, provide some information on distance.

The contributions of changes in target size, target vergence and relative disparity—and of global expansion or contraction in the background—to judgements of object motion during ego-motion in depth, were examined with simulations in which part of the information was omitted, or in which there was conflicting information from different sources. The change in velocity that is required for the target to appear to continue moving at the same speed after the simulated ego-motion was determined by asking subjects to report whether the target moved faster, at the same speed, or more slowly after the simulated ego-motion. If the velocity at which subjects reported that the target continues to move at the same speed is clearly different from the velocity that is appropriate for the simulation (i.e. if the required target velocity on the screen did not result in the angular velocity that the target would have if the observer had actually moved towards or away from a real moving object), it is concluded that the information that is normally used to account for ego-motion in depth is missing in that simulation.

METHODS

The experiments were conducted using an ATARI Mega ST 4 computer and either an ATARI SM 125 white monochrome monitor (frame rate, 71 Hz; image size, 22×13.5 cm; 640×400 pixels), a Sony KX-14CP1 Trinitron colour monitor (60 Hz; 23×17.5 cm; 640×200 pixels), or a BARCO colour projection system (60 Hz; 2.4×1.6 m; 640×200 pixels). Subjects looked at the image from a distance of either 35 cm (monitors) or 150 cm (projection system); so that the image filled $35 \times 22°$ of visual angle when presented on the monochrome monitor, $36 \times 28°$ for the colour monitor and $77 \times 56°$ for the projection system.

In the initial, monocular experiments, subjects looked at the monochrome monitor with one eye through a hole with a diameter of 15 mm. The target was a 1.25×1.25 cm random pixel array (50% light; 50% dark) that moved from left to right (at about eye level). Its initial velocity was 3 pixels per frame (about 12°/sec). The background consisted of a simulation of a wall of tiles, a striped floor and a shaded pillar (the latter being half-way between the observer's initial position and the wall). The luminance of the pixels was 3.0 and 0.015 cd/m^2 for light and dark pixels respectively. In the experiments using the projection system, subjects wore goggles which occluded one eye. The target was 14×14 cm and its initial velocity was 2 pixels per frame (about 17°/sec).

In the experiments providing information from stereopsis, different images were presented to the left and right eyes in succession, using the colour monitor and LCD shutter spectacles (Neucom Electronic GmbH). The luminance of light pixels was 10 cd/m^2 through the spectacles when the shutter was "open" (i.e. an average of 5 cd/m^2 per eye during the presentation). The initial target velocity was 3.6 pixels per frame (about 12°/sec). The pillar was omitted from the background.

All the experiments took place in the dark. In the initial monocular experiments, the subject looked at the screen though a hole in a box. The inside of the box was painted matt black and the end of the box opposite the hole fit tightly to the screen. At the low luminance levels used in the initial experiments, subjects could only see the stimulus itself. Nevertheless, the subjects were obviously aware that they were looking at a screen at a small, fixed distance (they had seen the equipment when they came into the room and could possibly get some impression of the distance from accommodation). The likelihood of an influence of accommodation was reduced by presenting the image on the large screen at a distance of 1.5 m. However, the light from the large image made it possible to detect the edges of the screen and some of the larger surrounding structures. The edges of the screen were also sometimes faintly visible in the binocular experiments (due to the absence of the box and the higher luminance), but the image itself obviously always provided a much more salient background.

The target appeared on the left half of the screen and started moving to the right [Fig. 1(a,b)]. Subjects had been instructed to follow the moving target with their eyes. The target moved at the initial velocity for between 500 and 600 msec; after which its velocity gradually changed (constant acceleration), to reach its final value after another 300 msec. The simulated ego-motion took place during this 300 msec transition period. The target then continued moving at its final velocity for another 500–600 msec [Fig. 1(c,d)]. The onsets of both the initial and the final period of target motion were signalled by tones.

In the initial experiments, the target disappeared, or was largely hidden from view by a simulated pillar, during the 300 msec during which the simulated ego-motion and the change in target velocity took place. The pillar was introduced because the change in target size gave the impression of target motion in depth (the additional change in velocity confused the inexperienced subject of a pilot experiment). It was omitted in the binocular experiments, because I myself (the first subject) frequently lost fusion of the target as it emerged from behind the pillar. The change in target size did not result in perceived target motion in depth in the (full) binocular simulations. The results of a binocular experiment in which the same image was shown to both eyes (experienced subjects; no pillar) demonstrate that the pillar itself is not responsible for the differences between the monocular and the binocular experiments (see Results).

The subjects' task was to indicate whether the target's final velocity was faster, the same, or slower than its initial velocity. They were simply instructed to judge the target's velocity, without any specifications on how to do so. None of the subjects had any difficulty performing this task (note that they were not in simulated motion during the actual intervals that were to be compared). Subjects were not instructed in more detail and not given any feedback on their performance, in order to obtain an as direct measure of the perceived motion as possible, avoiding unnecessary additional influences.

The final target velocity on each presentation depended on the subject's responses on previous presentations. A staircase procedure was used to find two values for the final velocity for each experimental condition: the lowest speed at which the target appeared to accelerate and the highest speed at which a reduction in velocity was observed.

For finding the lowest speed at which the target appeared to accelerate, the staircase procedure was as follows: if the subject reported that the target's final

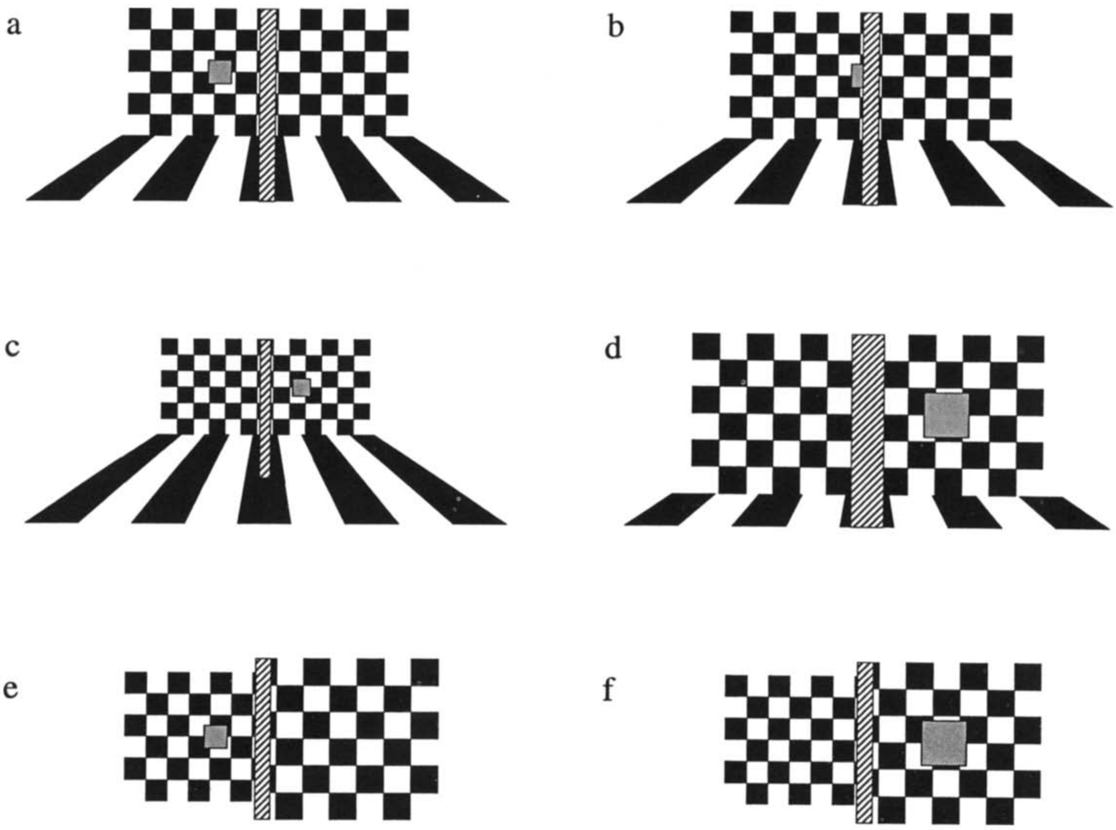

FIGURE 1. Schematic representations of two of the (monocular) stimuli that are used to examine the effect of simulated ego-motion on the perceived velocity of a moving target. The target moves from left to right until it disappears behind a pillar (a,b,e). When the target is behind the pillar, the image on the screen either changes in a manner simulating backward (c) or forward (d) motion of the observer, or else, the target size and velocity change in the same manner (f), but the background does not change (the surfaces at the two sides of the pillar can be considered to be at different distances from the start). In the latter case (e,f), the local spatial relationships are identical to those for the condition with simulated ego-motion (a–d), but there is no global optic flow to suggest that the observer has moved. The variable that is examined is the velocity with which the target must reappear from behind the pillar if it is to appear to continue moving at the same speed.

velocity was higher than its initial velocity, the target's final speed was decreased on the next presentation. If he or she reported that the final velocity was the same as the initial velocity, or that the target's final velocity was lower than its initial velocity, its final speed was increased on the next presentation. The magnitude of the increase or decrease was reduced (to 80% of the previous value) after each trial, until it reached a level that was negligible on our screen. The value onto which the staircase converged was taken as the transition point.

The highest speed at which the velocity appeared to decrease was determined in the same manner, except that reports that the final velocity was identical to the initial velocity resulted in a lower (rather than a higher) velocity on the next presentation (for additional details see Brenner, 1991a). Each transition point was determined three times for each subject. All staircases within one experiment ran simultaneously, with different ego-motions being presented in random order, so that the subject could not anticipate the simulated ego-motion.

The simulated ego-motion consisted of gradual motion (constant velocity) towards—or away from—the wall. The extent of the ego-motion was either one-eighth or one-quarter of the distance to the wall. The target's size (on the screen) after the ego-motion depends on the extent of the ego-motion, as well as the simulated distance of the target from the observer. In the initial monocular experiments, the simulated distance to the target was half of the distance to the wall (target just behind the pillar), three-quarters of the distance to the wall, or equal to the distance to the wall (target just in front of the wall). For the large screen, only the closest and furthest distance were used. With stereopsis, only the intermediate value was used (except for one case, in which the target was at the same distance as the wall and the magnitude of the simulated ego-motion was increased to obtain the same change in target size).

All subjects that took part in the experiments involving stereopsis had normal binocular vision (as assessed with a random-dot stereogram). Results for one stereo-blind subject with normal acuity through both eyes are presented separately. This subject could not detect the target in a random-dot stereogram at any of the tested disparities (between a crossed disparity of 3.16° and an uncrossed disparity of 1.32° of visual angle; target size 6°; pixel size 4 min arc). Furthermore, changes in target vergence simulating sinusoidal motion in depth, with an amplitude of one-third of the 35 cm viewing distance (0.5 Hz; constant target size), did not result in fluctuations in apparent size. He reported seeing the target move sideways, corresponding with suppression of his right eye.

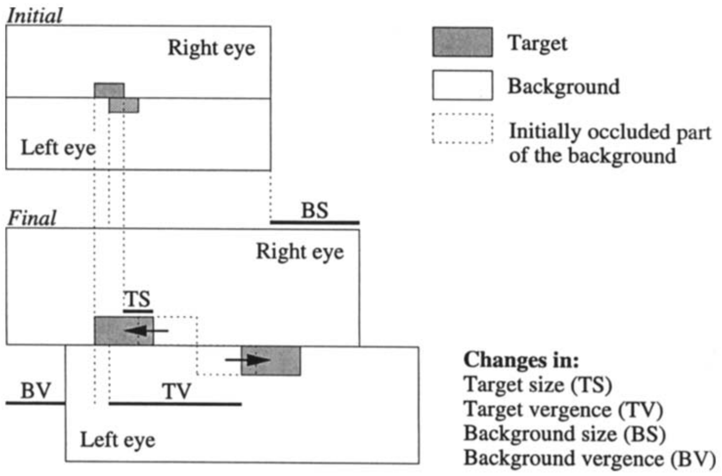

FIGURE 2. Schematic representation of the changes to the images presented on the screen (for each eye), as a result of simulated forward ego-motion, in the experiments with binocular stereopsis. The target is actually also moving to the right (not shown). Ego-motion forward results in changes in target and background size (expansion) and in target and background vergence. The difference between target vergence and background vergence is the relative disparity. The initial relative disparity provides information on the relative distances of target and background before the simulated ego-motion. The change in relative disparity is the difference between the changes in target and background vergence (TV-BV), or the difference between the displacements of the target relative to the background (rate of occlusion; arrows). If pursuit is perfect, ocular vergence coincides with target vergence.

Table 1 shows a (coded) list of the subjects that took part in each experiment. Each condition took about 1.5 hr. Subjects were encouraged to take breaks whenever they got tired and were free to stop at any time. They could always continue the experiment, at the point at which they stopped, on the next session. The monocular experiments were conducted before the binocular experiments; and the experiments on the small screen preceded those on the large screen. All subjects that took part in the binocular experiments were first tested with the full simulation. Otherwise, conditions within each group of experiments (initial monocular experiments; experiments with the large screen; binocular experiments) were presented in a more or less random order.

MONOCULAR EXPERIMENTS

The initial monocular experiments consisted of three conditions. In the first, the only difference between the two intervals was that the size of the target had changed. The target moved across a dark background; disappearing during the 300 msec that separated the initial from the final motion. In the second condition, a structured background was added to the simulation. The changes in target size were thus accompanied by global expansion or contraction, which specified that they were being caused by the subjects' own (simulated) motion. The target was hidden from view by the pillar during the 300 msec of simulated ego-motion.

Global expansion or contraction of the background implies that the direct surrounding of the target changes. As local relative retinal size may by itself have a strong influence on the perceived velocity (Epstein, 1978), the data for simulated ego-motion were compared to data from a third condition, in which the size of the "tiles" in the background was different at the two sides of the pillar [Fig. 1(e,f)]. In this condition, the target size and the size of the tiles directly adjacent to the moving target were identical to those for the simulated ego-motion (at each moment in time), but the background did not change during the presentation.

BINOCULAR EXPERIMENTS

In the experiments in which different images were shown to the two eyes to produce stereoscopic depth, each surface's position on the screen depended on the surface's simulated distance, the eye for which the image was intended and the distance between the subject's eyes. The target was visible (at the appropriate depth) for 3 sec before starting to move (the background was always initially simulated to be at the actual distance to the screen). All other conditions were as for the simulated ego-motion (second condition) in the previous set of experiments, except that the pillar was omitted, so that the target was visible during the simulated ego-motion. The simulated ego-motion was performed more slowly (the same simulated displacement took 600 rather than 300 msec) for three subjects in one experiment (see Results). The changes that occur when simulating motion of the observer in depth are shown schematically in Fig. 2.

In monocular experiments, global optic flow is required to specify that changes in the target's retinal image size are caused by ego-motion changing the distance to the target, rather than by the target's size changing (or by the target moving in depth). Whether global expansion and contraction influence the perceived target velocity when binocular stereopsis provides independent evidence that changes in the size of the retinal image of the target are due to changes in (simulated) distance, rather than changes in the (simulated) target size, was examined with a simulation in which there was

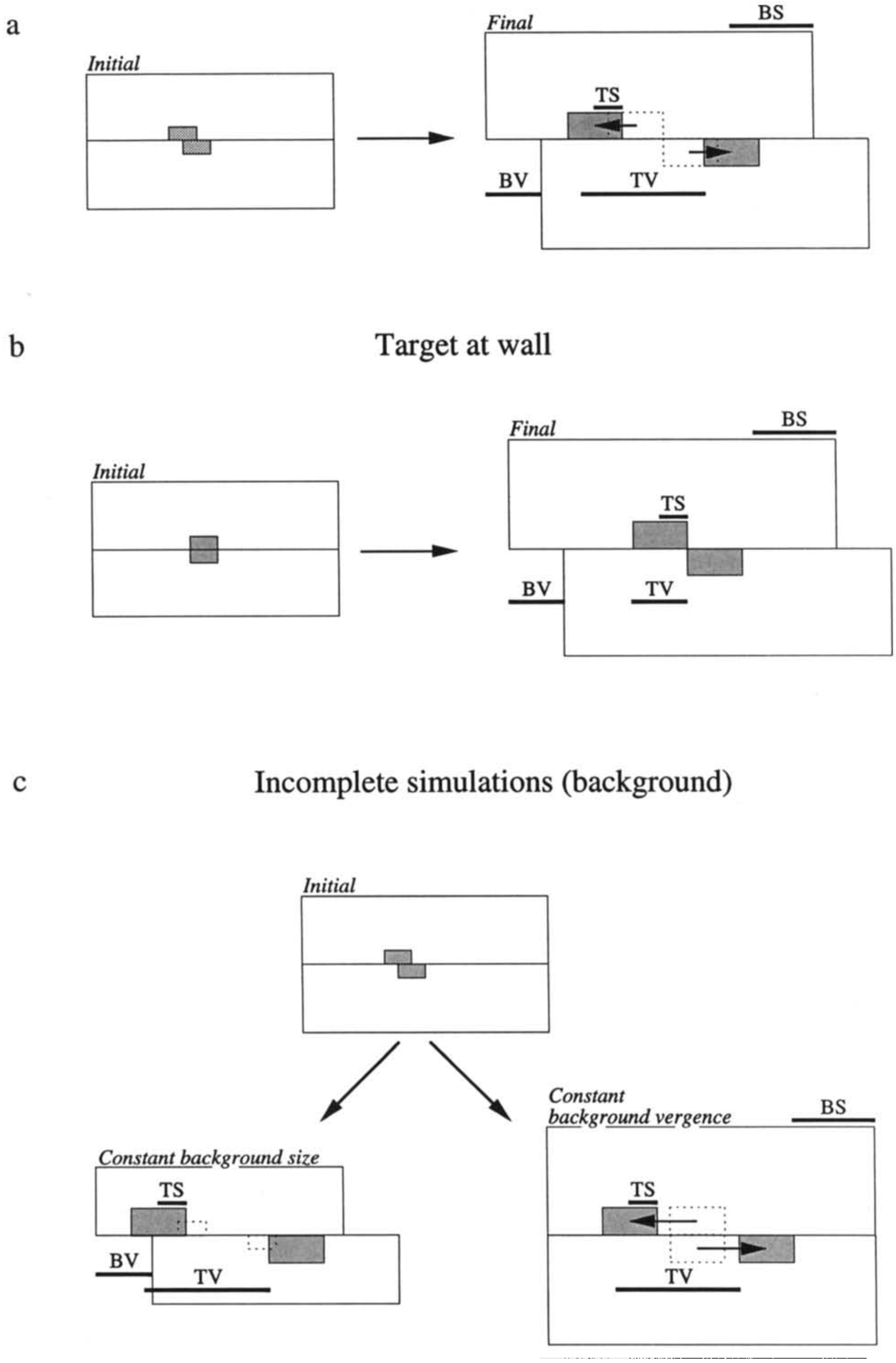

FIGURE 3. Schematic representation of the changes to the images presented on the screen as a result of simulated forward ego-motion (see legend of Fig. 2). (a) Complete simulation with target considerably closer to the observer than the wall. (b) Complete simulation with target at the same distance from the observer as the wall. (c) Incomplete simulations with target considerably closer to the observer than the wall, in which the background either did not expand in accordance with the simulated ego-motion (left) or was not presented at different positions for the two eyes in accordance with the simulated change in distance (right). In the latter case, relative disparity changes much more than it should (arrows).

no expansion or contraction in the background [Fig. 3(c)]. The background did shift for each eye; changing background vergence in accordance with the ego-motion that was being simulated. In a converse simulation, the background underwent the expected expansion or contraction, but it remained at the same place on the screen (for both eyes). In both cases, the target's position on the screen changed in the appropriate manner (so that in the second case, relative disparity changed at least twice as much as it should have).

To evaluate the contributions of changes in target size, in target vergence, and in relative disparity between target and background, separate simulations were made in which each was kept constant, while the others changed appropriately (Fig. 4). In the first case, the target simply did not change size (on the screen) as

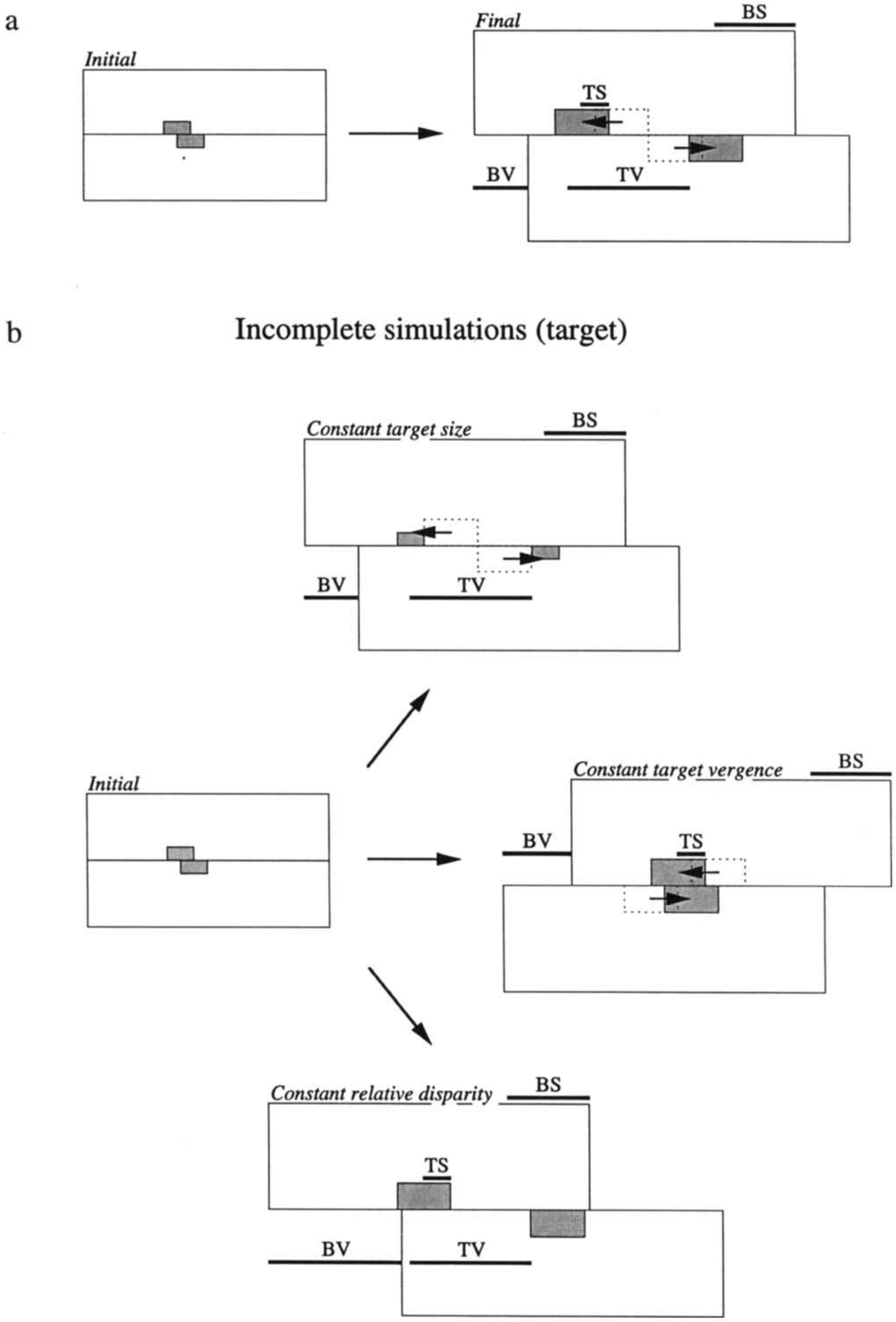

FIGURE 4. Schematic representation of the changes to the images presented on the screen as a result of simulated forward ego-motion (see legend of Fig. 2). (a) Complete simulation with target considerably closer to the observer than the wall. (b) Incomplete simulations in which the target either did not expand in accordance with the simulated ego-motion (top), or in which its position either on the screen (middle) or relative to the background (bottom) did not change in accordance with the simulated change in distance. When target vergence remained constant (middle), the images presented to each eye are identical to those in the complete simulation (a), but the images are displaced so that fixation of the target can be maintained without additional vergence eye movements. When relative disparity remained constant (bottom), the target did not shift relative to the background in either image, but the images did shift, so that ocular vergence was required to maintain fixation on the target.

its simulated distance changed. In the second, target vergence remained constant, so that subjects did not need to make (additional) vergence eye movements to maintain fixation of the target. To make relative disparity change in the expected manner, distance related shifts in the position of the target on the screen were replaced by (additional) shifts of the background of the same magnitude, but in the opposite direction. In the last case, relative disparity did not change, but the target's position on the screen (i.e. target vergence) changed appropriately (for each eye). Relative disparity was kept constant by shifting the background together with the target.

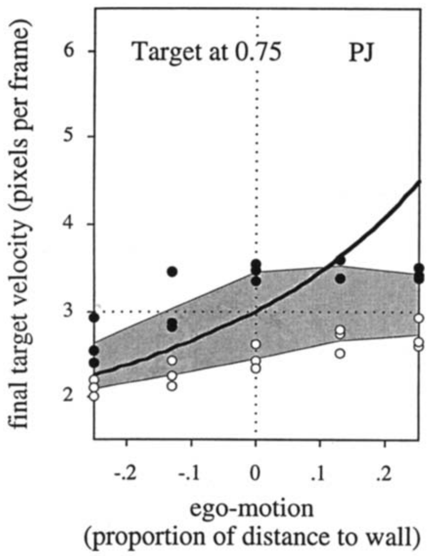

FIGURE 5. The outcomes of one subject's staircases for simulated ego-motion in depth (monocular; screen at 35 cm). Horizontal axis: simulated displacement of the observer as a proportion of the distance to the wall. Positive values correspond with motion forwards. Vertical axis: final velocity of the target (on the screen). The dotted horizontal line shows the initial target velocity. Solid symbols show the outcomes of staircases used to find the transition between no perceived change in velocity and a perceived increase in velocity. Open symbols for those between no change in perceived velocity and a decrease in perceived velocity. The range of target velocities for which the subject is under the impression that the target continues to move at the same speed is depicted by the shaded area. The thick curve shows the final speed with which the simulation predicts that the target should be set to move across the screen for it to appear to continue to move at the same velocity. Fractional velocities are presented by displacing the target by different numbers of pixels on consecutive frames.

RESULTS

Figure 5 shows results for simulated ego-motion in depth for one subject. The horizontal axis shows the extent of the simulated ego-motion, i.e. the total simulated displacement of the observer during the transition period. Positive values correspond with motion forwards. Negative ones with motion backwards. The amplitude of the simulated displacement of the observer, as well as the simulated initial distance to the target's path, are given as a proportion of the distance to the simulated wall. The vertical axis shows the target's velocity on the screen. The dotted horizontal line corresponds with the initial target velocity. The symbols show the outcomes of individual staircases.

Solid symbols are final target velocities for the transition between no perceived change in velocity and a perceived increase in velocity. Open symbols are final target velocities for the transition between no change in perceived velocity and a decrease in perceived velocity. There are three open and three solid symbols for each magnitude of ego-motion, because each staircase was performed three times. The range of target velocities for which this subject is under the impression that the target continues to move at the same speed (based on the average of the individual staircases) is shown as a shaded area. The final target velocity for which the target should appear to continue to move at the same speed, under the simulated conditions, is shown as a thick curve.

All subsequent figures show averages—of the ranges of velocities for which the target appears to continue to move at the same speed—of several subjects. Figure 6 shows the average data of six subjects for a target moving on a dark background. The target suddenly disappears, reappearing 300 msec later with a different size. The change in target size corresponds with a certain magnitude of simulated ego-motion at each simulated distance of the target. The three parts of the figure show the effect of the same simulated ego-motion for three different simulated initial distances of the target (although the data could be presented in one figure, as

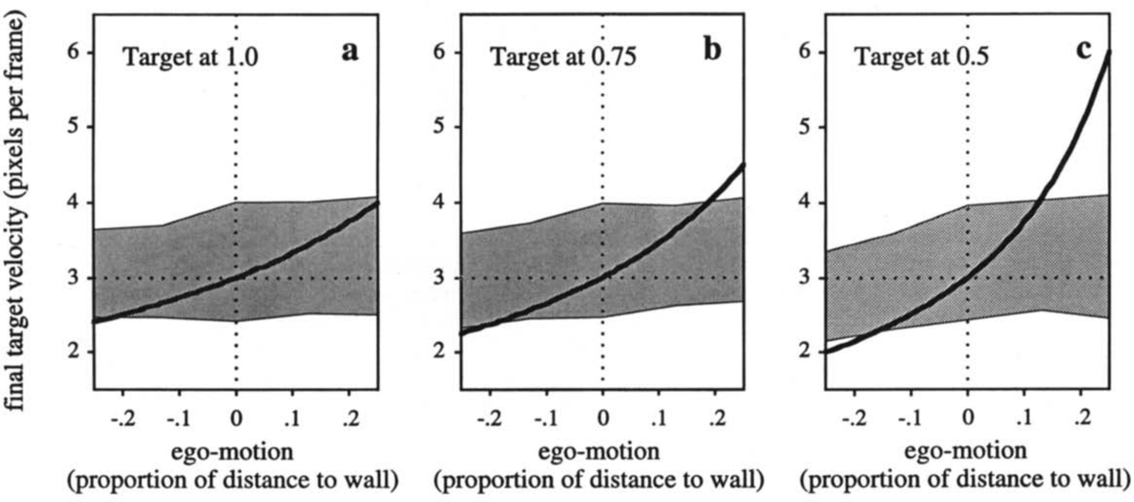

FIGURE 6. Influence of changes in target size, with no visible background, on the range of velocities for which the target appears to continue to move at the same speed. The target disappears, reappearing 300 msec later with the appropriate size (on the screen) for the specified change in distance between target and observer. The figure shows the mean range set by six subjects. The thick curve shows the speed with which the simulation predicts that the target should move across the screen after the change. The different parts of the figure are for different simulated distances of the target (the wall is not visible; results are presented in this format for comparison with the next two figures). Monocular presentation; screen at 35 cm. For further details see Fig. 5.

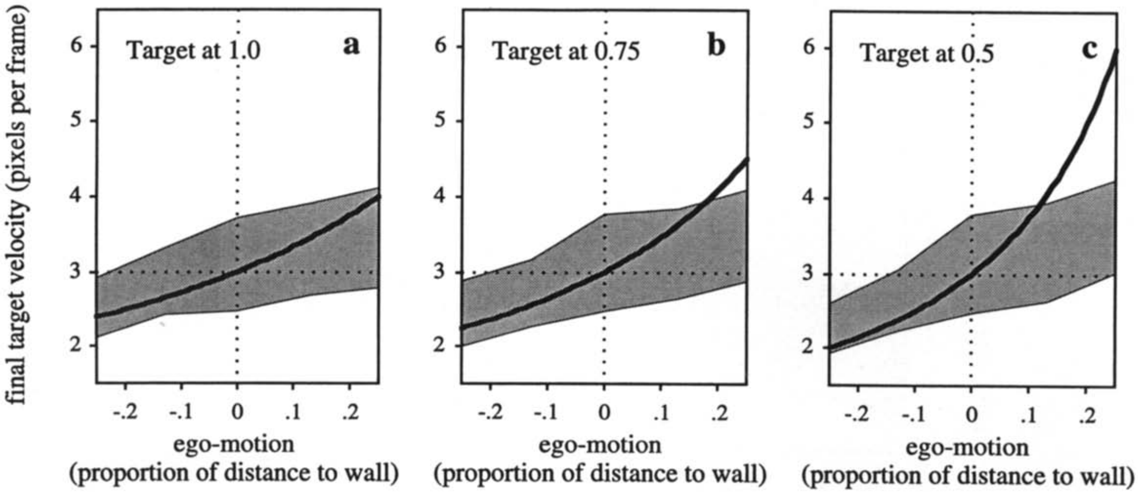

FIGURE 7. Range of velocities at which the target could move after the simulated ego-motion in depth, without it appearing to move at a different speed than it had before the simulated ego-motion. The figure shows the mean range set by the same six subjects as in Fig. 6. The thick curve shows the speed with which the simulation predicts that the target should move across the screen after the change. The different parts of the figure are for different simulated distances of the target (the distance of the target is evident from the change in size during the ego-motion). Monocular presentation; screen at 35 cm. For further details see Fig. 5.

a function of the change in target size, it is presented in this way for comparison with the other conditions in the following figures). The change in target size does sometimes appear to influence the perceived velocity, but this effect is very small. It is more evident for decreases (corresponding with simulated ego-motion backwards) than for increases in target size (see also Brown, 1931).

Figure 7 shows the range of final velocities for which the target appears to continue moving at the same speed when a background is added to the simulation [as in Fig. 1(a–d)] for the same six subjects. In this case, expansion or contraction in the background could indicate that the change in retinal target size is due to ego-motion, rather than to the target growing or shrinking. In the presence of such global optic flow, the results are closer to the prediction based on the assumption that the change in target size is due to a change in distance. However, the magnitude of the effect still falls short of the expectation; especially for simulated forward ego-motion.

Comparison with the control condition, in which the background consists of different sizes of tiles at the two sides of the pillar [see Fig. 1(e,f)], provides evidence that the global optic flow is indeed responsible for the increased effect of target size. In this control condition, the range of velocities for which no change in speed was perceived was almost unaffected by the change in target size (Fig. 8), refuting the hypothesis that differences between the sizes of the surfaces that the target occludes as it moves along are used to adjust the perceived velocity to ego-motion in depth.

Similar results were obtained when the image was projected on a much larger screen and viewed from a

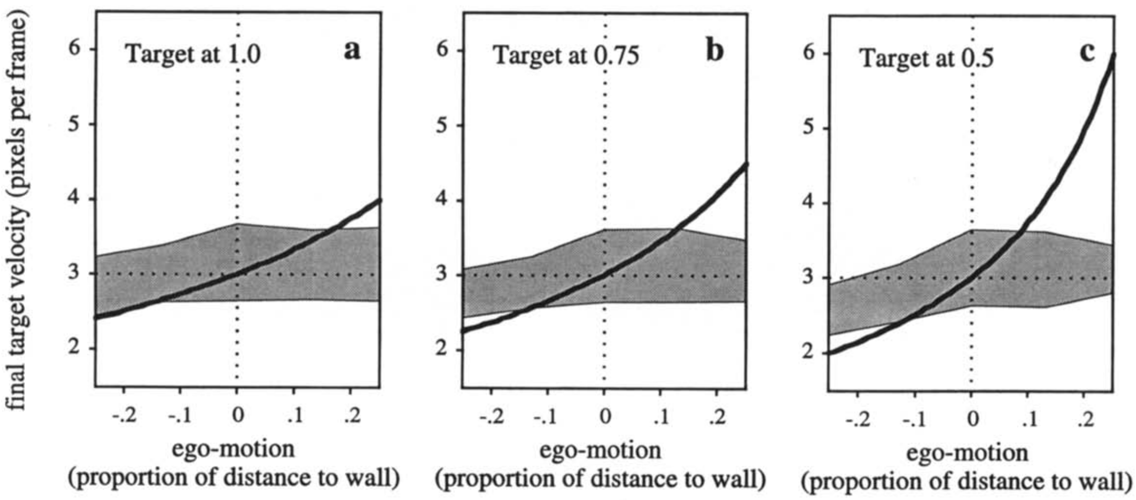

FIGURE 8. Range of velocities for which the target appeared to continue to move at the same speed in the control condition, in which the sizes of the surfaces adjacent to the target (and that of the target itself) were identical to those in the simulation of ego-motion, but in which the background did not change during the presentation [for further details see text and Fig. 1(f)]. The figure shows the mean range set by the same six subjects as in Figs 6 and 7. The different parts of the figure are for different simulated distances of the target. Monocular presentation; screen at 35 cm. For further details see Fig. 5.

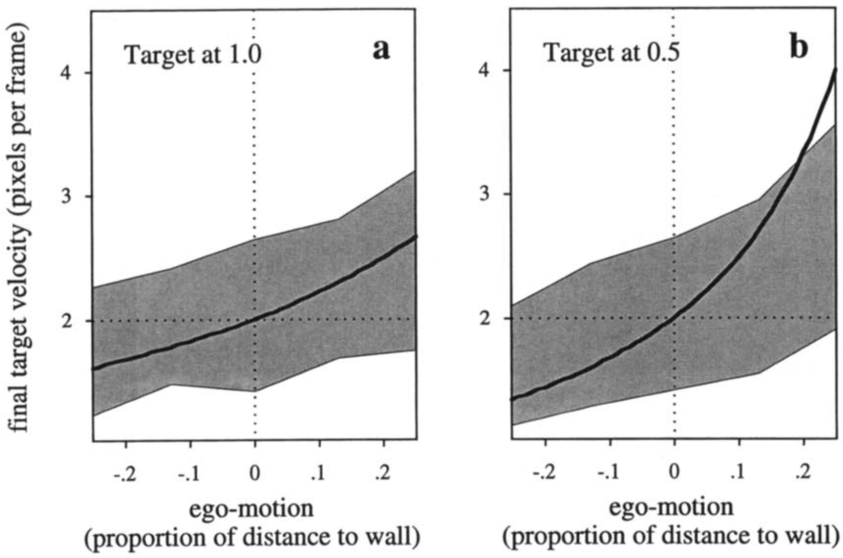

FIGURE 9. Range of velocities at which the target could move after the simulated ego-motion in depth, without it appearing to move at a different speed than it had before the simulated ego-motion (as in Fig. 7, but using the projection system). The figure shows the mean range set by four subjects (myself and three other subjects than those whose data are shown in the previous figures). The thick curve shows the speed with which the simulation predicts that the target should move across the screen after the change. Monocular presentation; screen at 150 cm.

larger distance. Again, a given change in target size had a much stronger influence when it was part of simulated ego-motion (Fig. 9), than in the control condition (Fig. 10). The results are very similar to those with the small screen, except that the range itself is larger. The larger range may simply be due to the results in Figs 9 and 10 being for different subjects than those of the previous figures (except for myself; see Table 1).

The results for monocular vision, particularly the data for simulated forward ego-motion shown in Figs 7 and 9, suggest that something is limiting the effect of the optic flow. The similarity between the results using the small and the large screens, makes it unlikely that the field of view or the absence of changes in accommodation are responsible. The most obviously unrealistic visual aspect of the simulation is that subjects are limited to looking with one eye. I therefore examined what would happen if (consistent) binocular stereopsis were added to the simulation [as in Figs 2, 3(a) and 4(a)]. The pillar was omitted, because fusing the image of the target as it reappeared from behind the pillar caused some problems (its simulated distance was apparently misjudged when it first reappeared from behind the pillar in the image presented to the right eye).

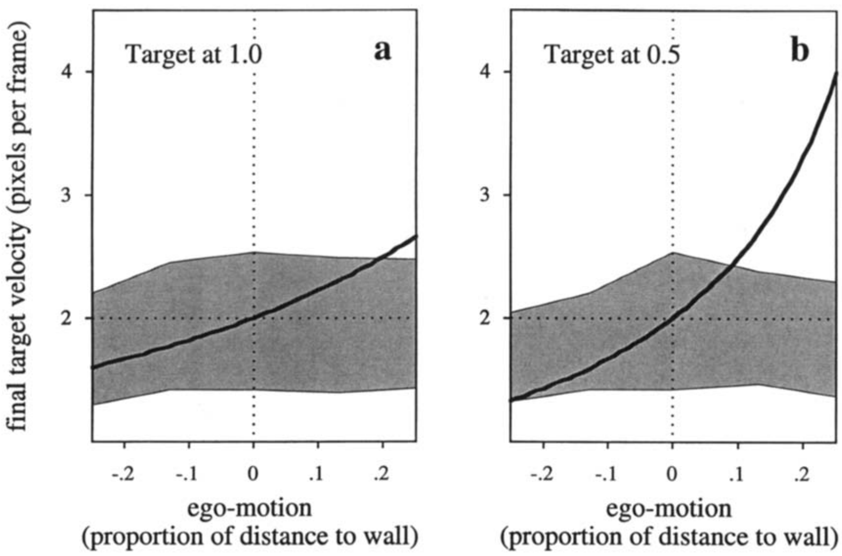

FIGURE 10. Range of velocities for which the target appeared to continue to move at the same speed in the control condition, in which the sizes of the surfaces adjacent to the target (and that of the target itself) were identical to those in the simulation of ego-motion, but in which the background did not change during the presentation (as in Fig. 8, but using the projection system). The figure shows the mean range set by the same four subjects as in Fig. 9. The different parts of the figure are for different simulated distances of the target. Monocular presentation; screen at 150 cm.

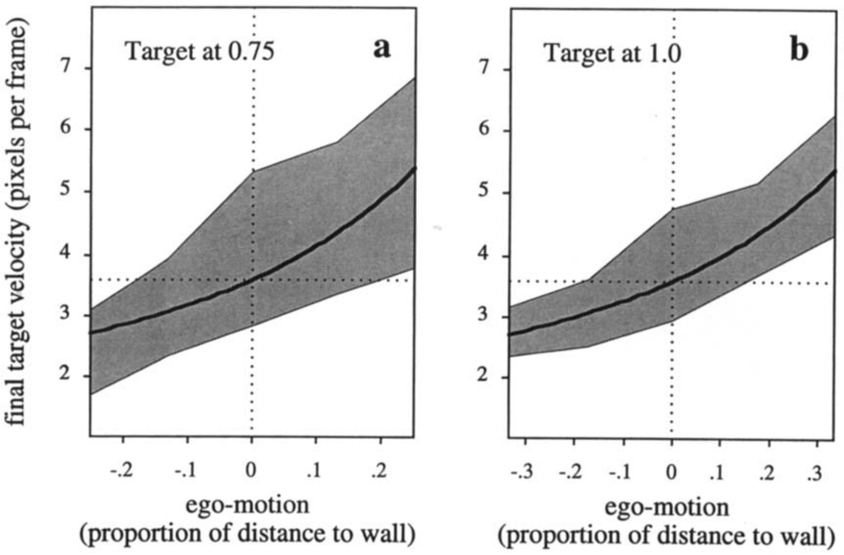

FIGURE 11. Range of velocities at which the target could move after the simulated ego-motion in depth, without it appearing to move at a different speed than it had before the simulated ego-motion, when the simulation was presented in stereoscopic depth. (a) Mean range set by nine subjects who did not see the target change size during the simulated ego-motion (myself and eight subjects who had not participated in the previous experiments). The simulated distance of the target is three-quarters of the distance to the wall. (b) Range set by three of these subjects (including myself), when the simulated distance of the target is equal to the distance to the wall [see Fig. 3(b)]. In the latter case, the extent of the simulated ego-motion was increased to obtain the same change in target size. Stereoscopic presentation; screen at 35 cm; no pillar.

An important effect of adding stereopsis became clear to me as soon as I performed the test myself; the target no longer appeared to become larger or smaller. Although we readily interpret expansion on television, or in the cinema, as changes in distance, we do notice the change in size on the screen. We are not fooled into believing that the object will move out of the screen and hit us. A real object that moves towards us does not appear to expand, although its image on our retina obviously does. In this sense, adding stereopsis made the simulation much more realistic.

Figure 11(a) shows the results for nine of the twelve subjects tested. These subjects (including myself) never had the impression that the size of the target had changed. The other three [data shown in Fig. 12(a)] found the task very difficult, often failed to fuse the target during the simulated ego-motion and reported that the target often appeared to change size. Moreover,

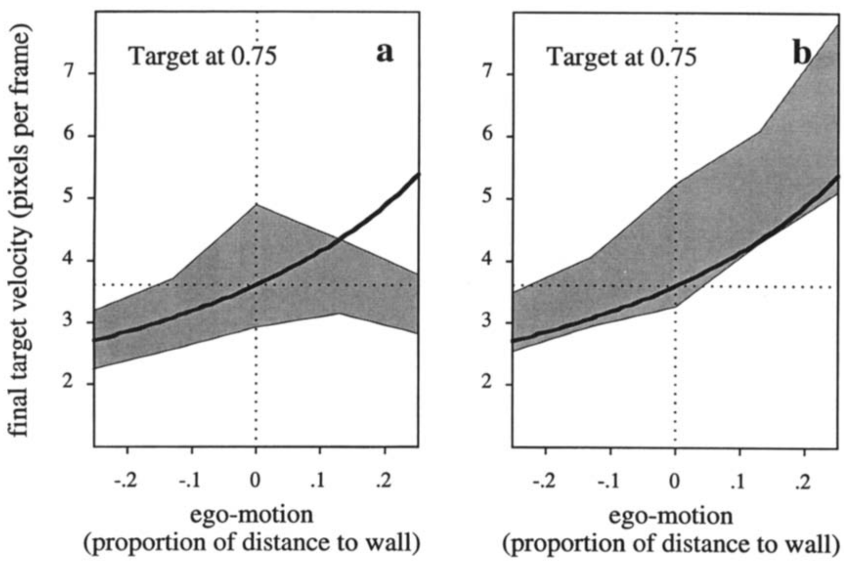

FIGURE 12. Range of velocities at which the target could move after the simulated ego-motion in depth, without it appearing to move at a different speed than it had before the simulated ego-motion, when the simulation was presented in stereoscopic depth [as in Fig. 11(a)]. (a) Mean range set by another three subjects, who were under the impression that the size of the target did change during the simulated ego-motion. (b) Range set by the same three subjects, when the simulated ego-motion took 600 rather than 300 msec, and the subjects no longer saw the target change size. At the lower velocity of ego-motion (the extent remained the same), these three subjects' responses were similar to those of the other nine subjects [Fig. 11(a)]. Stereoscopic presentation; screen at 35 cm; no pillar.

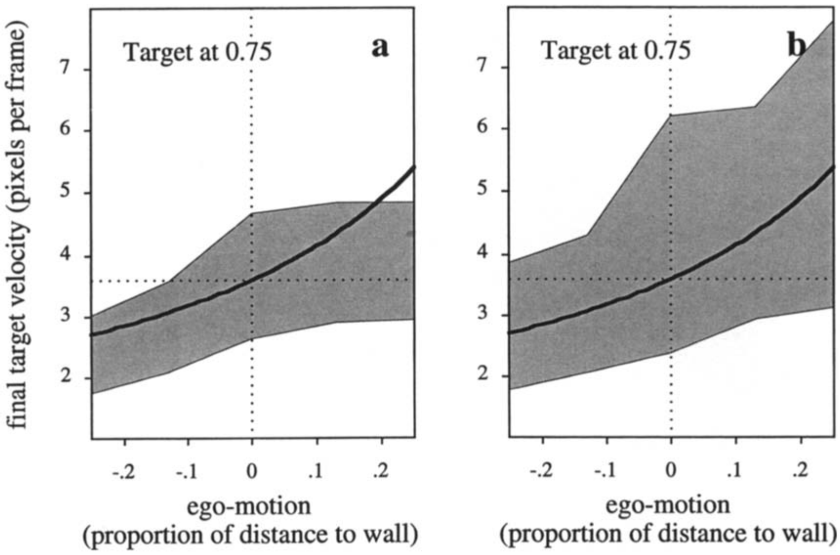

FIGURE 13. Range of velocities at which the target could move after the simulated ego-motion in depth, without it appearing to move at a different speed than it had before the simulated ego-motion, when the simulation was presented to both eyes without stereoscopic depth. (a) Data for six of the subjects of Fig. 11(a). (b) Data for one stereo-blind subject. The simulated distance of the target is three-quarters of the distance to the wall. The stereo-blind subject did not see the target change size during the simulated ego-motion. Binocular presentation; screen at 35 cm; no pillar.

the target would sometimes appear to move towards the subject, or away from him or her, during the simulated ego-motion. The obvious difference between these subjects' data [Fig. 12(a)] and that of the other nine subjects [Fig. 11(a)], suggests a relationship between ocular vergence, perceived change in size and perceived velocity. The paradoxical decrease in the required final target velocity with increasing simulated forward ego-motion in Fig. 12(a), is probably the result of the perceived motion of the target towards the observer.

Thus, adding stereopsis improved compliance with the simulation for some subjects, but not for others. This is probably related to the subject's abilities to make the required pursuit eye movements. Quite fast eye movements were required to maintain pursuit of the target (vergence of up to 12°/sec). When the three subjects who had seen changes in target size were re-tested with slower simulated ego-motion (taking twice as long to move the same distance; thus reducing the speed of the vergence that is required to maintain fixation on the target by half) they no longer saw the target change size and the final target speeds for which they reported no change in perceived velocity was as expected for the simulated conditions [Fig. 12(b)].

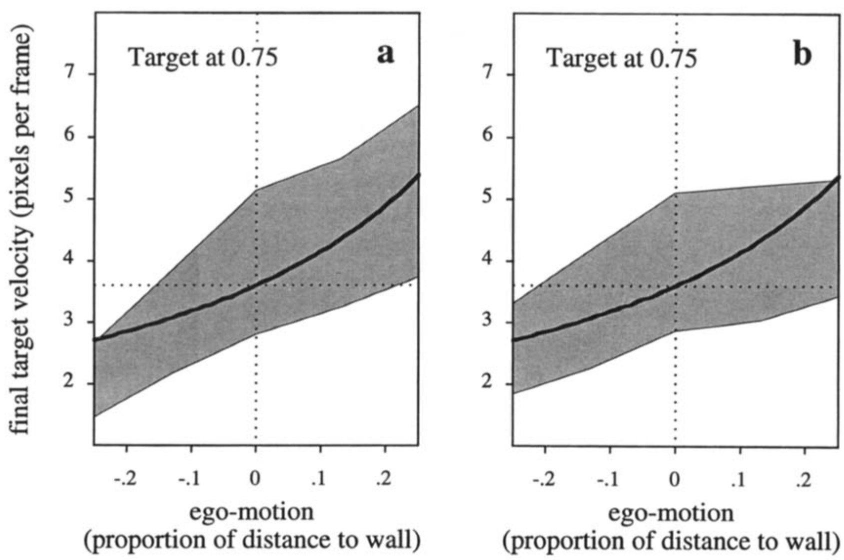

FIGURE 14. Range of velocities at which the target could move after the simulated ego-motion in depth, without it appearing to move at a different speed than it had before the simulated ego-motion. The target was presented in stereoscopic depth and its size changed appropriately. The background either [see Fig. 3(c)]: (a) underwent the expected global expansion or contraction, but its vergence did not change; or, (b) its vergence changed appropriately, but it did not undergo the expected concomitant global expansion or contraction. Data for six subjects from Fig. 11(a) [the same six as in Fig. 13(a)]. Screen at 35 cm; no pillar; target at three-quarters of the distance to the wall.

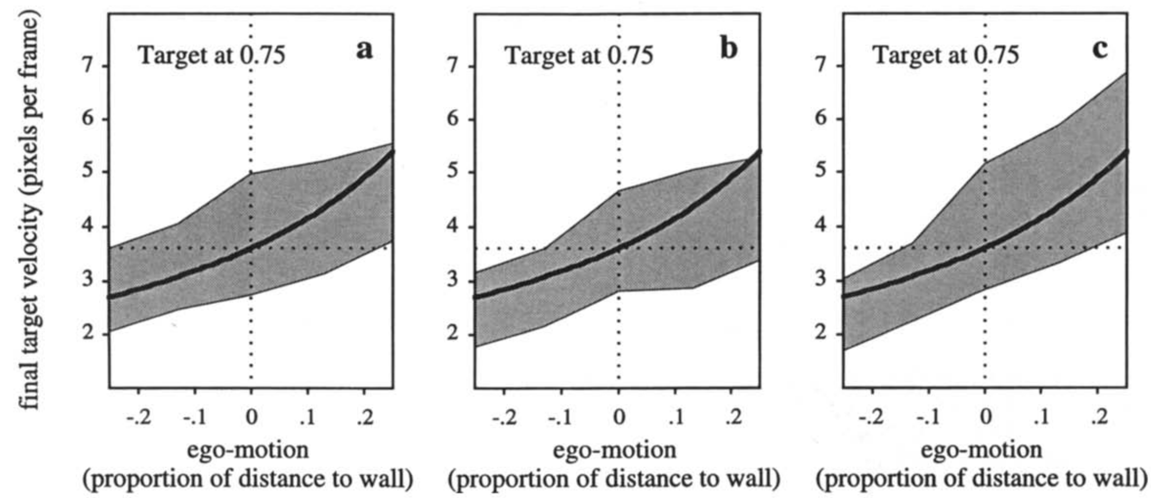

FIGURE 15. Range of velocities at which the target could move after the simulated ego-motion in depth, without it appearing to move at a different speed than it had before the simulated ego-motion. (a) Both target and background were presented in consistent stereoscopic depth, but the size of the image of the target did not change (so that it appeared to shrink as the observer approached it and to expand when the observer moved away). The background did undergo the expected expansion or contraction. (b) The distance between the target's position on the screen, for the two eyes, did not change (constant target vergence). Adequate relative disparity between target and background was maintained by shifting the background. The image reaching each eye is (almost) identical to that of a completely adequate simulation [e.g. that of Fig. 11(a)], but no vergence eye movements are required to maintain fixation on the target. (c) Relative disparity between target and background was kept constant. Again, this was achieved by shifting the background, so that target vergence remained at the appropriate value. In all three cases, the presentation was completely adequate until the simulated ego-motion started [see Fig. 4(b)]. Background vergence changed inadequately in both (b) and (c). Data for six subjects from Fig. 11(a) (see Table 1). Screen at 35 cm; no pillar; target at three-quarters of the distance to the wall.

Figure 11(b) shows the range of velocities for which the target appeared to continue moving at the same speed [for three of the subjects of Fig. 11(a)] for the same change in target size as in Fig. 11(a). In this simulation, the target was at the same distance as the wall, so that there was no relative disparity (or change in relative disparity) between the target and the wall [Fig. 3(b)]. The extent of the ego-motion was increased in order to get the same change in target size. The results are clearly in good agreement with the values that are expected from this simulation. This shows that changes in relative disparity between target and background are not necessary for accounting for ego-motion in depth. Conflict between changing size and expected changes in relative disparity may nevertheless influence the perceived target velocity when the target is not at the same simulated distance as the background.

Figure 13(a) shows results for binocular viewing without stereopsis (six subjects). There was no difference between the images presented to the two eyes; and no pillar. The results are similar to those for monocular viewing [Fig. 7(b)]. Thus, the absence of the pillar and the simple fact that subjects were allowed to use both eyes, cannot explain the difference between the monocular experiments and the experiments with binocular stereopsis. A stereo-blind subject's data for the binocular stimulus without stereopsis are shown in Fig. 13(b). The results are similar to those made by subjects with normal binocular vision for stimuli presented in full stereoscopic depth; rather than being similar to their monocular data. The stereo-blind subject did not observe any changes in target size.

Global optic flow influenced the results in the absence of stereopsis. Presumably, the flow of the background made subjects more readily inclined to interpret the change in the size of the image of the target as a change in distance; rather than as an actual change in size. Whether global optic flow plays the same role when target vergence specifies that the change in target size is the result of a change in distance to the target is examined with two incomplete simulations [see Fig. 3(c)].

In the first condition (constant background vergence), the position of the background on the screen remained identical for the two eyes despite the simulated ego-motion, but the background did undergo the expected global expansion or contraction. The results are shown in Fig. 14(a). In the second condition (constant background size), the background did not expand or contract when motion of the observer was simulated, but its position changed for each eye to maintain adequate background vergence [Fig. 14(b)]. In both cases, the target's size and its position for each eye (target vergence), changed appropriately for the simulated ego-motion.

For simulated forward motion of the observer, the change in target size was only completely accounted for in the presence of expansion or contraction of the background. The global optic flow is, therefore, still important. Moreover, the excessive change in relative disparity during simulations of backward ego-motion in

TABLE 1. Overview of the subjects that participated in each experiment and of the variability within individual subject's replications

	Subjects*	Figure†	Within subject variability‡
Initial monocular experiments			
Changes in target size only	**1,2,3,4,5,6**	6	8.4
Full simulation	**1,2,3,4,5,6**	7	6.9
Static control	**1,2,3,4,5,6**	8	6.3
Large screen			
Full simulation	**1,7,8,9**	9	6.4
Static control	**1,7,8,9**	10	6.9
Binocular experiments			
Full simulation (target at 0.75)	**1**,*7,8,***10,11,12,13,***14,15,16,17,18*	11a	7.4
Full simulation (target at 1.0)	*1,10,14*	11b	
Slower full simulation (0.75)	*7,8,16*	12	
Flat image (same for both eyes)	**1,10,11,12,13,***14*	13a	6.6
Flat image (stereo-blind subject)	*19*	13b	
Constant background vergence	**1,10,11,12,13,***14*	14a	6.3
Constant background size	**1,10,11,12,13,***14*	14b	6.4
Constant target size	**1,10,11,12,13,***15*	15a	6.5
Constant target vergence	**1,10,11,12,13,***15*	15b	6.2
Constant relative disparity	**1,10,11,12,13,***15*	15c	6.5

*Quantitative comparisons were restricted to the subjects indicated with bold numbers.

†The figures show the average data of all subjects.

‡The standard deviations of the three replications for each subject, velocity of ego-motion, transition (to slower or faster perceived motion), and distance of the target (when more than one was used), were averaged across subjects, velocity of ego-motion, transitions and distances; and are presented as a percentage of the initial target velocity.

which background vergence remained constant (relative disparity is more than doubled by not moving the background appropriately), may even have led subjects to overestimate the change in distance [left side of Fig. 14(a)].

The separate contributions of changes in target size, in target vergence, and in relative disparity, were examined in three more simulations, much as described above for the influences of global optic flow and background vergence. In these simulations, either target size, target vergence, or relative disparity was kept constant [Fig. 4(b)]. The others changed in accordance with the simulated ego-motion.

The results are shown in Fig. 15. Target vergence is clearly important [Fig. 15(b)]. When the increase in target size was accompanied by global expansion and an increase in relative disparity, but not by a change in target vergence, the set velocity clearly did not increase as expected from a simulation of forward ego-motion. Similarly, increases in target size evidently contribute to velocity judgements during ego-motion in depth [Fig. 15(a)]. The results for simulations with constant relative

TABLE 2. Results of analyses of variance comparing the transition points* in various experiments, with those of comparable full simulations (see text and Table 1), taking the effects of subject,† simulated ego-motion,‡ and simulated target distance§ into account

	Main effect of experiment		Interaction between experiment and ego-motion		Interaction between distance and ego-motion		Interaction between distance, ego-motion and experiment	
Transition in perceived velocity	Slower	Faster	Slower	Faster	Slower	Faster	Slower	Faster
Target size only (monocular)	NS	$P < 0.001$	$P < 0.001$	$P < 0.001$	NS	$P < 0.01$	NS	NS
Static control (monocular)	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	NS	NS
Static control (large screen)	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$	NS	NS	$P < 0.01$	NS
Flat image (binocular)	$P < 0.001$	$P < 0.001$	$P < 0.001$	$P < 0.001$				
Constant background vergence	$P < 0.001$	$P < 0.001$	$P < 0.05$	$P < 0.001$				
Constant background size	$P < 0.05$	$P < 0.001$	$P < 0.001$	$P < 0.001$				
Constant target size	$P < 0.05$	$P < 0.001$	$P < 0.001$	$P < 0.001$				
Constant target vergence	NS	$P < 0.001$	$P < 0.001$	$P < 0.001$				
Constant relative disparity	NS	$P < 0.05$	NS	NS				

*The transition from no change in perceived velocity to a slower or faster perceived velocity.

†For an overview of the subjects included in the analysis see Table 1. All subject main effects, subject by experiment interactions, and subject by ego-motion interactions are statistically significant ($P < 0.001$); as are all subject by experiment by ego-motion interactions ($P < 0.05$).

‡The main effects of ego-motion are all significant ($P < 0.001$).

§The only significant effects of distance that are not shown in the table are: a distance main effect ($P < 0.001$) and a distance by subject interaction ($P < 0.05$) for the initial experiments; and a distance by subject ($P < 0.01$), a distance by subject by experiment ($P < 0.05$), and a distance by experiment ($P < 0.001$) interaction for the experiments using the large screen; all for the transition to a faster perceived velocity for the comparison between the full (monocular) simulation and the static control.

NS, not significant ($P > 0.05$).

disparity [Fig. 15(c)] did not differ from those for complete simulations [Figs 4(a) and 11(a)]. Changes in relative disparity are therefore not crucial for adjusting the perceived velocity to ones own movements in depth.

For simulated backward ego-motion, the results were usually quite similar to the prediction of the simulation. The only cases in which the data were clearly closer to the real velocity than to the simulated velocity are the monocular experiments in which there was no background, and those with a static background with different sizes of elements at the two sides of the pillar. Otherwise, changes in either target size or target vergence were interpreted as changes in distance. For ego-motion forwards, both target size and target vergence appear to have to change together, for the simulated change in distance to be adequately accounted for.

STATISTICAL ANALYSIS

In addition to plotting the data as shown in Figs 6–15, the differences between experiments were also evaluated using analyses of variance. The results of each experiment were compared with results for the same subjects in experiments providing as complete simulations of ego-motion as possible. The subjects included in the analysis are indicated by bold numbers in Table 1. Four factors were included in the statistical analysis: experiment; simulated ego-motion; simulated target distance (monocular experiments only); and subject. The outcome of the comparisons is summarized in Table 2.

The main issue in the present study is obviously the interaction between the experiment and the simulated ego-motion. This was always significant ($P < 0.05$) except for the comparison between the full binocular simulation and the simulation in which relative disparity remained constant (by shifting the background together with the target during the simulated ego-motion). Even the small difference between the full binocular simulation and the simulation in which background vergence remained constant is statistically significant.

The large number of significant effects and in particular of most effects in which the factor "subject" is involved, implies that both the replications of the outcomes of individual subjects' staircases and the differences between subjects' responses to different simulations, were quite reliable. For the questions addressed by the present study, however, the consistency between subjects' responses is obviously of more interest than are the differences between subjects.

The different target distances that were simulated in the monocular experiments did affect the influence of simulated ego-motion on the perceived velocity (several significant interactions between distance and ego-motion), but this effect was much smaller than would be appropriate under the simulated conditions (Figs 7 and 9). Possibly as a result of this, the relationship between target distance and ego-motion did not seem to depend on the nature of the simulation: subjects responded differently to changes in target size in different experiments (significant interactions between experiment and ego-motion), but additional variations in the change in target size (indicating differences in simulated target distance) could not be shown to influence velocity judgements in a consistently different manner in different experiments (only one significant interaction between experiment, ego-motion and target distance).

The last column of Table 1 shows a measure of the variability within each experiment. The values are averages (over ego-motions, distances, transitions and subjects) of the standard deviations within replications (there was no correlation between the average velocities and the standard deviations). They are expressed as percentages of the initial target velocity. The variability may be slightly higher in the absence of a background that can act as a reference for judging the angular velocity ("target size only"), but there is no indication of the variability being larger for incomplete simulations (the slightly larger variability in the full binocular simulations may be because this was the first experiment for four of the five subjects that were included in the statistical analysis; see Methods). Apparently the task itself could be performed quite reliably under all conditions. The lack of increased variability in incomplete simulations indicates that the different results are not due to the perceived velocity becoming ambiguous under such conditions, but are a true reflection of the influence of the omitted aspects of the simulation on the perceived velocity.

DISCUSSION

This paper examines how simulated ego-motion in depth (perpendicular to the target's trajectory) influences the perceived velocity of a target of ocular pursuit. Three parameters appear to be involved: global expansion or contraction, changes in target size and changes in target vergence. For other directions of ego-motion, at least one more parameter is involved: translation of the background (Brenner, 1991a).

Before looking into the factors involved in making velocity judgements independent of ones own movements in more detail, several general issues are discussed. The first is that inadequate simulations seldom show flat responses. This suggests that a compromise is sought that minimizes the discrepancies between various depth cues (Rogers & Collett, 1989). If so, then the magnitude of the deviation from the velocity that is predicted by the simulation, can indeed be considered as a direct measure of the importance of the cues that are absent in that simulation.

The next issue is that almost all of the figures show averages of several subjects. There are very large differences between subjects for each condition, resulting in the highly significant influences mentioned above and in Table 2. This is presumably mainly because subjects have to report on a subjective impression; does the target continue moving at the same velocity—or does it move faster or more slowly—in the second part of the presentation. Some subjects are inclined to report that the target moves at the same speed unless they are certain that this is not so, whereas others report that it moves faster or more slowly unless they are sure that it moves at the same speed. This leads to large differences between subjects' data (see Brenner, 1991a), although each subject's transitions are very reproducible (Fig. 5 and Table 1). Despite considerable differences between subjects' results, the influence of the simulated ego-motion is very similar for all subjects tested [except in the cases in which this is explicitly mentioned; see Figs 12 and 13(b)]. The variability between subjects' data is not shown in the figures, because it reflects differences in the way in which subjects interpret the task, rather than differences in the way in which the variables under examination influence their velocity judgements.

As already mentioned, the deviation from the predicted value was always more evident for simulated forward motion (i.e. for a growing target), than for simulated motion backwards. This difference is too large to be fully accounted for by the required changes in the orientations of the eyes being larger for the approaching stimuli. It could, perhaps, be due to a combination of this factor and expected changes in accommodation (see below). Another possibility is that there may be a fundamental asymmetry between perception of increases and decreases in velocity (Brenner, 1991b).

The simulation

A striking aspect of the simulation was that although none of the subjects reported having had a sensation of actual ego-motion, they did correct for it in their judgements of the target's velocity. This shows that the correction for ego-motion, when judging object motion, is independent of the actual sensation of ego-motion. Stimulation of large, peripheral parts of the visual field may be required to obtain a sensation of ego-motion (Johansson, 1977). The equipment I had at my disposal prevented me from increasing the angular extent of the stimulation much further, because the number of pixels does not increase, so that a larger field of view results in a lower spatial resolution (and therefore less accurate representations of target motion). This is not crucial, however, because adding stereopsis to the presentation on the computer screen was sufficient for subjects to adjust their perceived velocity almost perfectly to the simulated ego-motion; although none of the subjects had a sensation of actually having moved. Subjects actually generally either explicitly reported having seen a *simulation* of ego-motion, or reported having seen the whole image come closer (without specifying whether this was due to simulated ego-motion or to motion of the rest of the environment).

Accommodation

An inadequacy in all the simulations in which the observer moved in depth, is the absence of depth related changes in accommodative state (Ciuffreda & Kenyon, 1983; Semmlow & Hung, 1983). The fact that subjects' results do comply with the simulated changes in distance when stereopsis is consistent with the optic flow, proves that changes in accommodation are not crucial. However, the failure to comply with the simulated ego-motion in the monocular experiments, despite the fact that there could be no real conflict with information from stereopsis, could be an indirect result of accommodative vergence.

Accommodative stimulation results in a transient vergence response when in conflict with retinal disparity, and in a sustained response when there is no such conflict; such as in monocular viewing (Semmlow & Venkiteswaran, 1976). In the monocular experiments of the present study, retinal blur may have initially driven the occluded eye to become adequately oriented for a target at the actual distance of the screen. During the simulated ego-motion, therefore, the orientation of the eyes will not correspond with the distances specified by the optic flow.

The hypothesis of a conflict between eye orientation and optic flow could explain why the monocular results are most similar to the prediction when the simulated target distance coincides with the distance to the screen [target at the same simulated distance as the wall; Figs 7(a) and 9(a)]. It also explains why the monocular data hardly differs from binocular data without stereopsis [Fig. 13(a)]. However, even when the initial simulated distance of the target corresponds with its actual distance, the results are not quite as expected [Figs 7(a) and 9(a)]. Apparently, the initial orientation of the eyes is not the only factor.

Vergence

From optic flow alone, the distance of the target (relative to that of the wall) is only specified when the observer "moves" in depth. A "wrong" initial assumption (e.g. on the basis of accommodation) results in conflict once the ego-motion begins. With binocular stereopsis, the (relative) distance of the target is available to the subject from the start, so that this problem does not arise. However, even when the initial depth relationships, the initial eye orientations and the images presented to each eye were completely adequate, but target vergence remained constant during the simulated ego-motion [so that no ego-motion related vergence eye movements were required to keep looking at the target with both eyes; Fig. 4(b)], subjects did not experience the simulation as being adequate [Fig. 15(b)]. Thus it is not sufficient for stereopsis to inform the subject on the depth relationships before the ego-motion [Figs 14(b) and 15]. The target vergence must actually change together with the changes in target size.

The changes in the image presented to each eye were identical for the original simulations with stereopsis [Figs 4(a) and 11(a)] and for the simulations with constant target vergence [Figs 4(b) and 15(b)]. The difference must therefore have to do with the fact that unpredicted changes in target vergence result in the target's image moving in opposite directions on the two retinas; with the resulting retinal disparity inducing changes in the orientation of the eyes (vergence eye movements). The distance of the target could be accounted for on the basis of the retinal signals that elicit the vergence eye movements, of oculo-motor signals related to the ensuing vergence eye movements, or of some intermediate signals.

Three of the twelve subjects that were shown the complete stereoscopic simulation only set the velocity as predicted when the velocity of the simulated ego-motion was reduced. Their reports of temporary double vision (in the initial tests), suggests that their oculo-motor signals were inappropriate. Thus, actually maintaining fixation on the target by making vergence eye movements appears to be essential for adjusting its velocity to its change in distance. Nevertheless, ocular vergence need not be directly responsible for adjustments to the perceived velocity, because the interpretation of retinal disparity in terms of distance is also disrupted if the retinal disparity becomes too large (resulting in loss of fusion).

The difference between the rotation of the two eyes is not sufficient to account for the change in distance, because the angle of ocular vergence that is required to maintain fixation on an approaching or receding target is different—for the same change in (relative) distance—for different orientations of the eyes. However, the fact that the two eyes' movements (Bains, Cadera & Vilis, 1991) and orientations (Van den Berg, Van Rijn & Collewijn, 1992) are not independent, suggests that there is an intermediate signal that drives both eyes simultaneously towards a target's position in three-dimensional space. Such a signal could provide the necessary information for adjusting velocity judgements to the change in distance, by combining information from the images in the two eyes with information on the orientations of the eyes.

Target size

Changes in retinal target size induce small (transient) vergence eye movements (Erkelens & Regan, 1986). The signal that is responsible for these vergence eye movements could also be responsible for the (modest) influence of changes in target size (alone) that were found in this study (Fig. 6). However, this is unlikely to be the only explanation for the influence of target size on the perceived velocity, because it cannot account for the reasonable agreement between the prediction and the results for simulated backward ego-motion in Figs 7 and 13(a), unless the contracting background increases the ocular divergence induced by the target becoming smaller considerably (despite the arising conflict with retinal disparity); while background expansion does not even nearly have an equally strong influence on ocular convergence. The perceived velocity is therefore probably not directly related to changes in ocular vergence.

Changes in the target's retinal image provide sufficient information for adjusting the magnitude of the object's perceived velocity to the simulated ego-motion. The stereo-blind subject obviously had to base his decisions on changes in retinal target size [Fig. 13(b)]. Although the other subjects did not base their decisions exclusively on changes in retinal target size, it is clear from the results that changes in target size did influence the perceived velocity, and that changes in the size of the target's image were essential; even when there was sufficient information from stereopsis [Fig. 15(a)]. Thus, changes in both target size and vergence are used.

The retinal disparity that is caused by changes in target vergence is continuously counteracted by ocular vergence (providing a reason not to rely on the magnitude of retinal disparity as a measure of distance). However, if the target is pursued reasonably accurately, sudden changes in retinal target size, as a result of target motion, should be accompanied by changes in retinal disparity. The absence of changes in retinal disparity, when target size changes substantially and rapidly (as was the case in many simulations used in the present study), may be used to distinguish between changes in the size and changes in the distance of the target. This is consistent with the findings of the present study, in that the perceived velocity was adequate whenever subjects reported that the target did not change size (although the image on the screen did change size).

The hypothesis that retinal disparity is important, but its magnitude is not, provides an alternative to postulating that ego-motion in depth is accounted for on the basis of the signal that drives the eyes. Whether retinal information alone (target size and retinal disparity) is used to account for ego-motion in depth when judging the velocity of a target of smooth pursuit, or whether the oculo-motor information (signal that drives the eyes) also contributes to the perceived velocity, may depend on how the velocity of the target itself is judged. The perceived target velocity can depend on retinal as well as on oculo-motor signals (Brenner, 1991b). Target distance could therefore be accounted for on the basis of retinal signals alone whenever perceived target velocity depends exclusively on relative motion; and on oculo-motor signals when target velocity is judged on the basis of the version eye movements that are needed to pursue the target. Such differences could be responsible for the unequal requirements in simulations of forward and backward ego-motion.

Global optic flow

That global expansion and contraction in the background play an important role in accounting for ego-motion in depth is evident from a comparison of Figs 7 and 8, Figs 9 and 10 and of the two parts of Fig. 14. From (monocular) target expansion alone, no distinction can be made between the observer moving towards the target and the target moving towards the observer. When there is no background, the only reason to discard the latter possibility is that moving objects generally do not suddenly change their direction of motion for no apparent reason. On the other hand, vestibular information may tell us that we ourselves are stationary (as is indeed our subjective impression). A logical conclusion is that the size of the target has changed.

When there is a background, this background is generally assumed to be stationary, so that global expansion or contraction indicates that the observer has moved. Global visual information can sometimes even suppress vestibular input concerning ego-motion when the two are in conflict (Lishman & Lee, 1973). In the present study, the global expansion or contraction presumably made sure that subjects interpreted the changes in target size as resulting from changes in distance (due to ego-motion). The fact that global expansion or contraction is even essential in binocular presentations, with adequate target vergence and relative disparity, suggests that we do not rely too heavily on binocular stereopsis (or vergence eye movements) in this respect.

CONCLUSION

It appears that the changing distance of the target is derived from a combination of changes in target size and target vergence. Only when the two change correspondingly is the velocity set according to the prediction of the simulation, and does the target not appear to change size. Moreover changes in target size and target vergence are only adequately accounted for, when judging objects' velocities, if accompanied by global optic flow in the surrounding. Global expansion or contraction specifies that the observer has moved (displacement); just as translation of the background has previously been shown to indicate that the subject has turned (his eyes).

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