Is precise discrimination of low level motion needed for heading discrimination?

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Normal observers judge heading well both when moving in a straight line and when moving along a curved path. Judgments of curved path motion require depth variations in the scene while judgments of straight line heading (pure translation) do not. Here we show that a stroke patient who is impaired in low level 2D motion discrimination tasks and cannot accurately judge 3D structure from motion can accurately judge heading for straight line self-motion. This patient is impaired in judgments of curved path self-motion. This suggests that accurate heading judgments for observer translation do not require accurate 2D motion perception or 3D reconstruction of the scene. Judgments of curved path motion appear more dependent on accurate 2D motion perception. *NeuroReport* 15:000–000 © 2004 Lippincott Williams & Wilkins.

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INTRODUCTION

A person moving through the world must judge his own direction of motion accurately enough to avoid obstacles and reach his destination. Psychophysical studies have shown that human observers judge their direction of motion very well both when moving in a straight line [1–5] and when moving on a curved path [6]. *A priori*, one might expect that these judgments depend on accurate perception of 2D image speed and direction. However, perception of heading for observers moving in a straight line appears to be remarkably tolerant of noise in the speed of the image velocities, although it is less tolerant of noise in the direction of these velocities [7]. This suggests that accurate low level speed discrimination may not be requisite for these judgments. In contrast, the ability to judge direction of motion in the presence of rotations appears to be sensitive to noise [8], so it may be that this aspect of heading perception is more reliant on low level motion perception.

Another aspect of heading perception is its relationship to depth variation in the scene. Observers moving in a straight line make accurate heading judgments in the absence of depth variation in the scene [1]. Accurate judgments of curved path motion, however, require depth variation in the scene to disambiguate the pattern of motion from that of observer motion in a straight line. Observers make large errors in heading estimates when there is no depth variation in the scene [1]. To take advantage of the depth variations, models for computing heading in the presence of rotation must use techniques that may be more sensitive to noise in the low level motion estimates. These include differential models, motion parallax models and error minimization models (see [9] for a more complete discussion of these models). Template models [10] that pool information over a large area of the scene may be somewhat less sensitive to noise. Some models use depth variation explicitly in the computation of curved path motion and simultaneously compute the relative distance to surfaces in the scene [11–14]. This raises a question as to whether heading perception is related to scene reconstruction and whether scene reconstruction is required for computing heading. To examine the dependence of heading judgments on low level motion perception and the relationship between heading and scene reconstruction, we studied the visual motion perception abilities of a patient, R.A., who is impaired on some aspects of low level motion perception. In particular we examined R.A.'s ability to judge straight line and curved path motion and his ability to judge (3D) structure from motion. This research has been previously published in abstract form [15].

PATIENT AND METHODS

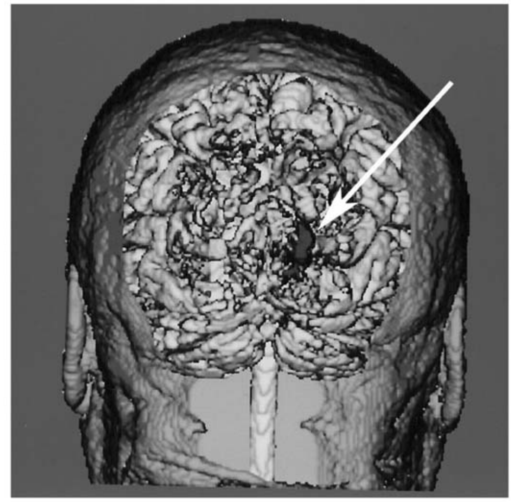
The patient: R.A. is a right handed man who suffered a right hemisphere cerebrovascular accident which resulted in a transient mild left-sided weakness from which he recovered within 2–3 weeks. He also complained of visual perceptual deficits associated with the perception of direction and speed of motion. A detailed description of the lesion and the low level motion deficits has been published previously [16]. The pertinent results for this study are summarized here. At the time of the testing and the data reported here, R.A. was 66 years old. R.A. and the normal controls gave informed consent to participate in the research study, conforming to the Boston University Human Subjects Committee requirements.

Visual fields were examined by both Goldmann and Humphrey perimetry. Both tests confirmed a left homonymous inferior quadrantopia which, however, resolved in a year. Eye movements (saccades and smooth pursuits) and fixation were normal as measured in neuro-opthalmological studies and in our laboratory using the Ober-2 (Premobile Inc. Needham, MA). The MRI revealed an infarction, predominantly cortical, involving the right occipital lobe and measuring $\sim$3 cm in its inferiosuperior dimension and $\sim$2 cm in its wider dimension. The lesion involves a portion of the caudal and medial part of the cuneus (CN), a portion of the superior and caudal part of the lingual gyrus (LG) and a portion of the most rostral and medial part of the occipital pole (OP) in the right occipital lobe. Since the detailed analysis of R.A.'s lesion has been published elsewhere [17], here we will illustrate his lesion on the 3D reconstruction of the brain (Fig. 1a) and on the inflated brain (Fig. 1b) which provide an accurate and intuitive visualization of the location. The lesion is probably centered on the human homologue of cortical area V2, known to be involved in aspects of motion processing [16,20]. R.A.'s visual perceptual abilities were evaluated during weekly visits to our laboratory at Boston University for a period of 2.5 years. The data reported here were obtained 19 months after his CVA accident. Here we briefly summarize previously published results [16,17]. Color discrimination (with Farnsworth-Munsell 100 Hues test) and contrast sensitivity for detection and contrast discrimination of both moving and static gratings were normal. On the Random dot stereo test using a Julesz anaglyph he was able to distinguish that something was there but was unable to make out the form: the star was a teddy-bear, and the triangle was a pitcher. R.A. also showed a normal ability to discriminate 2D form, spatial relations and orientation [16]. In tests performed at 2 and 20 months after the CVA accident, R.A. showed impairment in low level motion perception [16]. Data from these previously published studies are re-plotted here (Fig. 2). R.A. was significantly impaired in his ability to discriminate speed (Fig. 2a) and direction (Fig. 2b) of 2D motion in the left hemifield. He was also impaired in both hemifields in judgments of motion direction using a motion coherence task developed by Newsome and Pare [21] (Fig. 2c). These deficits did not change significantly between the two testing periods at 2 and 20 months [16].

Experiment 1. 3D structure from motion: In this experiment we tested the ability of R.A. to discriminate a pattern of motion representing a 3D structure from an unstructured motion pattern and compared the responses to those of normal observers.

In all tests stimuli were generated and presented using a Macintosh Quadra. Stimuli were shown in the center of the CRT and subjects were required to fixate on a small fixation mark shown at 2° eccentricity at midline level. The display consisted of two random dot cinematograms presented simultaneously one above the other in the center of the CRT. Each subtended $6.7 \times 6.7°$ with a dot density of 2.8 dots/deg^2. One of the two cinematograms portrayed a transparent cylinder revolving around a vertical axis with an angular rotation rate of 35 deg/s. The other cinematogram contained an unstructured stimulus generated by corrupting the velocity vectors present in the structured display and thereby destroying their local spatial relationship. The spatial positions of the structured and unstructured fields (top and bottom) were randomly assigned. Both the structured and the unstructured displays were generated by 50 frames, each displayed for 45 ms. This sequence was repeated for the duration of the display (2 s). Using a two alternative forced choice (2AFC) procedure, subjects were asked to indicate which of the two cinematograms looked more like a rotating cylinder. The proportion of structured field was systematically manipulated by corrupting the trajectory of a predetermined proportion of the velocity vectors, using a 2-down, 1-up staircase procedure. Threshold represented the proportion of the structured motion required by a subject to discriminate reliably between the unstructured and the structured display. We tested two conditions and each was repeated for infinite point lifetime (immortal) and finite point lifetimes of 400 ms and 200 ms.

(a)



(b)

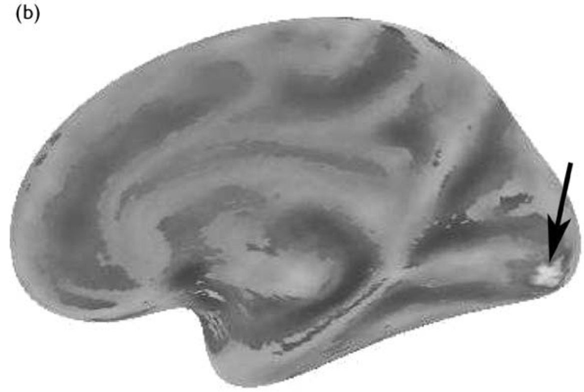


Fig. 1. (**a**) 3D reconstruction of the brain and lesion using MRX software package. The skin is partially removed to expose the brain and the lesion (the dark patch indicated by the white arrow). (**b**) The lesion is depicted on the inflated brain (Free Surfer software [18]). R.A.'s structural MRI was registered in Talairach space [19]. The lesion (bright patch indicated by the black arrow) involves the human equivalent of areas V1 and V2 (medially). See [20] for more detail on the methods.

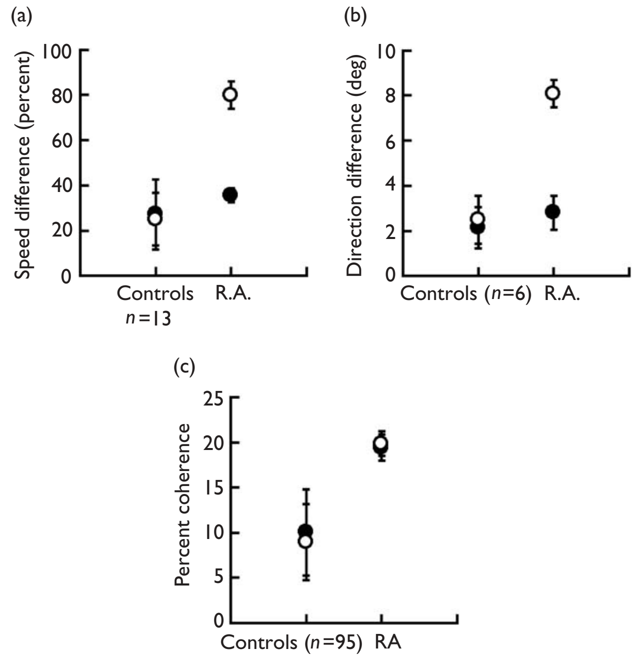


Fig. 2. Results of low level motion tests [16]. Open and filled symbols show the results for the left and right visual hemifields respectively. Data for R.A. was collected 2 months after the CVA accident. (**a**) Speed discrimination. The data show the percent speed difference required to determine which of two fields contains faster moving dots. (**b**) Motion direction discrimination. The graph shows the direction difference required to distinguish a left or right directional deviation from vertical motion. (**c**) Motion coherence task. The data show the percentage coherent dot motion required to distinguish direction of motion of coherently moving dots.

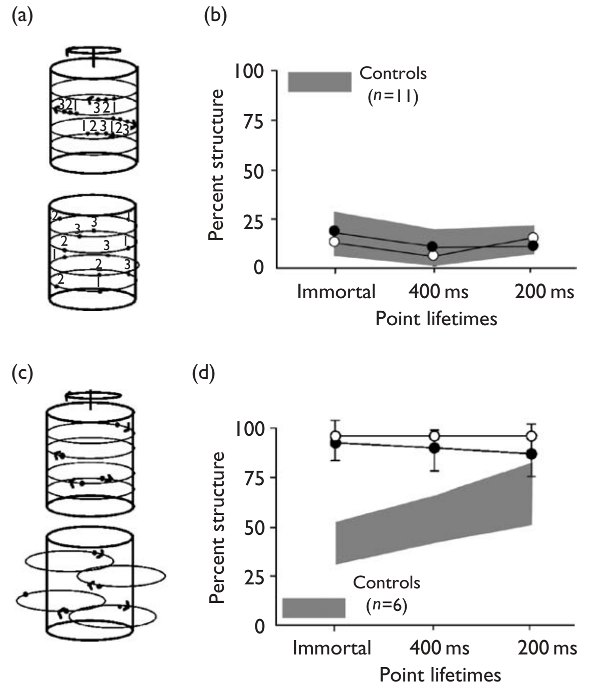


Fig. 3. Results of 3D structure from motion tests. (**a**) Diagram of temporal shuffling paradigm. The top cylinder shows dot positions in order for 100% structure. The lower cylinder shows the dots shuffled for 0% structure. (**b**) Results of the temporal shuffling experiment. Shaded region depicts the range of responses for normal subjects. Open and filled circles indicate R.A.'s responses for the task on the left and right halves of the visual field, respectively. (**c**) Diagram of spatial shuffling paradigm. The top cylinder shows 100% structure and the lower cylinder shows 0% structure. (**d**) Results of the spatial shuffling experiment. All symbols are as in (b).

In condition 1, temporal shuffling (shown schematically in Fig. 3a), some proportion of the velocity vectors in the structured display are temporally shuffled. That is, the order in which the animation frames in the structured display are presented is randomly distorted. The unstructured stimulus presents a pattern of temporally scrambled vectors. Condition 2, horizontal offset, is shown schematically in Fig. 3c. In this condition all the dots travel along a cylindrical path. The dots that corrupt the structure of the cylinder move with the same angular velocity along a circular trajectory of the same radius as the stimulus, but their rotation axis is horizontally offset to the left or right of the stimulus' axis of rotation. Condition 2 is a more stringent test of the ability to perceive structure from motion than condition 1. In condition 1 it is possible that subjects may distinguish between the two cylinders based on temporal frequency differences rather than perceived 3D structure. Condition 2 eliminates the temporal frequency difference between the two cylinders, so that subjects may not use this as a cue for their responses.

Experiment 2. Judgment of heading for straight line motion: The next two experiments tested R.A.'s ability to judge heading for straight line motion (Experiment 2) and curved path motion (Experiment 3). In experiment 2 The stimulus consisted of a dynamic random dot field displayed in a square aperture subtending $20 \times 20\ \mathrm{deg}^2$. The motion of the field of dots simulated what the observer would see if approaching two transparent planes of dots at a distance of 400 and 1000 cm. The simulated motion of the observer was pure translation. The simulated observer speed was 200 cm/s and the direction varied with uniform probability between extreme values of 5° to the left and right of the center of the display. Subjects were instructed to fixate on a mark placed at 2° off the left or right border of the display at the horizontal midline. Observers watched a motion sequence for 800 ms, at the end of which a vertical line appeared at a given horizontal angle from the true heading.

In a 2AFC task subjects were asked to indicate whether their heading was to the right or to the left of the vertical line. The angle between the heading and the target line was varied according to a two-down one up staircase procedure (12 reversals). The threshold angle for accurate heading judgments was calculated as the average of the reversal values, excluding the first two.

Experiment 3. Judgment of heading for curved path motion: The display consisted of dynamic random dots whose motion simulated the observer's motion toward a 3D cloud of points ranging in distance between 400 and 1500 cm from the observer. In a single run of the experiment ten conditions were shown in random order. In five of the conditions the observer had a translational speed of 200 cm/s and a heading of 0° (i.e. toward the center of the screen), and the rotation rate was 1, 2, 3, 4 or 5 deg/s. The other five conditions simulated observer translation only, with headings of 2, 4, 6, 8 or 10° from the center of the screen. These values were chosen so that the 2D image speeds in the translation cases would be similar to those in the corresponding rotation cases. In a 2AFC procedure subjects indicated whether or not their self-motion contained a rotational component (in which they were moving on a curved path). Each condition was presented 10 times.

RESULTS

The results of temporal shuffling (Fig. 3b) show that R.A. performs as well as controls. The average threshold for distinguishing the structured from unstructured cylinder was 11.4% and 12.7% for R.A. in the left and right halves of the visual field and 13.8% for controls. In contrast, results for the horizontal offset condition (Fig. 3d) show that R.A. was highly impaired compared to normal subjects. R.A. needed nearly 100% structure to identify the 3D cylinder for all point lifetimes tested (average of 96.5% in the left visual field and 92.0% in the right), while normal subjects needed 44.9%, 56.1%, and 68.0% structure for the immortal, 400 and 200 ms point lifetimes, respectively. Thus, when temporal frequency cues were unavailable, R.A. could not reliably perceive 3D structure from motion.

The results of Experiment 2 show that R.A. performed as well as normal subjects for this task (Fig. 4). The threshold angle for normal subjects was 2.38 and 2.08° for the left and right visual fields, while for R.A. these were 2.92° in the left (impaired) visual field and 1.65° in the right (unimpaired) visual field. R.A.'s performance was well within the range of normal subjects. In Experiment 3 (Fig. 5) normal subjects were able to distinguish the curved path display from straight line motion reliably for rotation rates ≥ 3 deg/s. The average percentage of correct responses for this group were 95, 95 and 90% for rotation rates of 3, 4 and 5 deg/s respectively. Below 3 deg/s, normal subjects could not distinguish straight from curved path heading very well (53 and 85% correct responses for rotation rates of 1 and 2 deg/s), performing at about chance for the 1 deg/s rotation rate. While R.A. performed similarly to normal subjects for the unimpaired (right) side of the visual field, he performed much more poorly for the impaired (left) side of the visual field, performing above chance at only one rotation rate (60% correct for rotation rate of 2 deg/s) and at or below chance for all other rates of rotation.

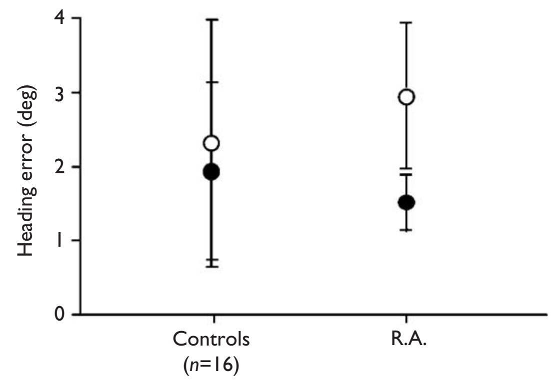


Fig. 4. Results of straight line heading experiment. Open and filled symbols show the results for the left and right halves of the visual field, respectively. Error bars indicate 1 s.d. above and below each data point.

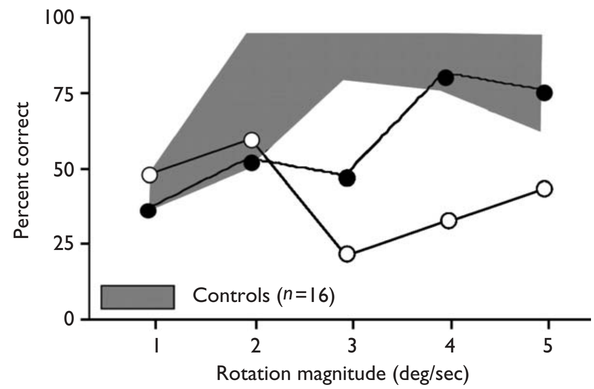


Fig. 5. Results of the curved path heading experiment. Symbols are the same as in Fig. 3b.

DISCUSSION

The results of the experiments reported here show an interesting dichotomy between judgments of straight line and curved path motion. R.A. was highly impaired in low level 2D motion tasks, and yet, surprisingly, was able to judge straight line heading as well as normal observers. This suggests that heading perception for observers moving in a straight line does not require accurate low level motion perception. In contrast, R.A. performed much worse than normal subjects when asked to distinguish curved path from straight line motion. So, while R.A. could accurately judge his motion on a straight path, he could not judge curved path motion. This implies that perception of curved path motion requires a more accurate computation of the low level image speed and direction.

This result for straight line heading is consistent with results from psychophysical experiments, in which judgments of straight line heading were tolerant to noise in the speed of the 2D image velocities [7]. Although the psychophysical experiments did not show an ability to maintain accurate heading judgments in the presence of large amounts of directional noise in the velocity vectors, our results suggest that straight line heading judgments do not require highly accurate perception of the direction of the 2D image velocities. One might predict from this that straight line heading judgments of normal subjects would tolerate a fair amount of directional noise in the velocity field. This prediction remains to be tested by systematically varying the amount of perturbation of velocity vectors and testing how well subjects can still judge straight heading (Sikoglu, Vaina, and Royden, in preparation). Because perception of curved path motion requires depth variation in the scene and the ability to make use of the resulting velocity differences throughout the visual field, the dependence of these judgments on accurate 2D image motion makes sense. Models that explicitly use velocity differences [11,12,22], or rely on error minimization [13,14], or other comparisons of neural responses [23] all require a fairly accurate measurement of the 2D image motion to compute heading in the presence of rotations. One would imagine that template models [10] would also require reasonably accurate 2D velocity input in order to distinguish templates tuned to straight line motion from those tuned to motion containing a rotational component. The results presented here suggest an interesting test of these various models. If they accurately describe the neural mechanism for human heading perception, then they should be tolerant to noise in speed and direction for straight line heading judgments, but may be less tolerant when computing heading in the presence of rotations. Several studies of heading perception suggest that the 3D construction of scene layout can be beneficial when judging direction of motion, particularly for motion containing rotations [24,25]. This raises the question of whether 3D scene reconstruction is required for accurate heading perception. The results of these experiments clearly show that it is not required for judgments of straight line heading. R.A. was severely impaired on the 3D structure-from-motion tasks, but judged straight line heading as well as normal subjects. On the other hand, R.A. was impaired in judgments of curved path motion, suggesting the possibility that scene reconstruction is important for this task. Alternatively, this result could mean that both judgments of 3D structure from motion and judgments of curved path motion require accurate 2D image motion perception and so both are impaired as a result of the deficit in this low level motion perception.

CONCLUSION

A patient with impaired ability to judge 2D image motion and 3D structure from motion is able to judge his direction of motion well for straight line motion. This implies that judging heading for motion on a straight line does not require scene reconstruction or a highly accurate perception of 2D image velocities. In contrast, this patient was impaired in judgments of motion on a curved path, suggesting that these judgments depend on more accurate judgments of 2D image motion.

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