11. Parametric Measurements of Optic Flow by Humans

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1 THEORETICAL FRAMEWORK

Motion pervades the visual world (Marr, 1982). This is so not only because images in nature are unlikely to be static, but also because motion constitutes a rich source of information to understand those images. The strategy that the brain uses to measure motion in images has been extensively studied and many theories have been proposed. The challenge has been to design a biologically plausible theory that will predict all motion phenomena and work on real images. With this approach, Yuille and Grzywacz (1998) have proposed a theoretical framework for visual motion that accounts for most existing psychophysical and physiological experiments. The theory proposes that the visual system fits internal models to the incoming retinal data, selecting the best models and their parameters. The fit begins with a measurement stage that performs local estimates of motion, such as local velocity (Bravo & Watamaniuk, 1995). These local estimates, which are noisy (Shadlen & Newsome, 1998) and sometimes ambiguous (Movshon et al., 1985), are then clustered (in a space of measurement variables) into regions whose boundaries correspond to motion boundaries. This clustering is performed by a number of competitive processes corresponding to different motions. The theory proposes that different types of tests can compete to perform this clustering. For example, the grouping can be done by either parametric or non-parametric tests. The former test will try to detect familiar motions defined by prior statistics-of-natural-scenes models, while the latter will allow the visual system to deal with general types of motion that may never have been seen before.

Although the knowledge of motion statistics in natural images is important to understand what these familiar motions are, some theoretical
studies can shed light over this issue. Koenderink and van Doorn (1976) have shown that any complex flow field generated by motions of planar surfaces can be decomposed into several elementary components including translation, expansion, and rotation. Because small patches of natural surfaces are approximately planar, it may be possible to perform this decomposition for small portions of natural scenes. Therefore, the visual system could take advantage of this decomposition by incorporating these elementary components as models for the analysis of motions in real scenes (Figure 1). Experimental justification for this hypothesis comes from psychophysical experiments showing the existence of looming and rotation detectors (Regan & Beverley, 1985; Freeman & Harris, 1992; Morrone et al., 1995; Snowden & Milne, 1996) and from physiological studies showing that there are cortical neurons sensitive to translation, rotation, expansion, and spiral motion (Maunsell & Van Essen, 1983; Tanaka & Saito, 1989; Tanaka et al., 1989; Duffy & Wurtz, 1991a,b; Graziano, et al., 1994; Loge et al., 1994). However, to meet the requirements of the framework these specialized neural mechanisms should work parametrically. For example, a parametric model for rotation would have a center of rotation and an angular velocity as parameters to be determined.

It is known that humans can precisely estimate parameters of translational motions such as direction (De Bruyn & Orban, 1988) and speed (McKee, 1981; Johnston et al., 1999). However, little is known about other types of motions. Some pieces of evidence can be found in recent investigations showing that the visual system would not be using just the estimates of local velocity to evaluate the speed of rotation and the rate of expansion (Geeseman & Qian, 1996, 1998). For instance, an expansion appears to move faster than a rotation, even if the local linear velocities at corresponding points of the images are equal. This effect was explained by arguing that the subject does not perform the task by using the local velocities but some form of global velocity (Clifford et al., 1999). The subject could be comparing the rate of expansion with the angular velocity of the rotation. Why a subject sees expansion faster than rotation is a fascinating question, which however, is outside of the scope of this article. For us, what is important is that these motions are seen different, because the rate of expansion, the angular velocity or both of these parameters are not equally perceptually scaled.

Whether the mechanisms that are specialized in the detection of Koenderink and van Doorn's elementary components are metric is the question that we will address in this chapter. Moreover, we will discuss how the visual system can compute these complex motion parameters from real scenes.

2 MEASURING ROTATIONAL MOTION

Werkhoven and Koenderink (1993) suggested that human subjects cannot make precise estimates of angular velocity from rotational motions. These authors found that such estimates were systematically biased towards linear velocity. Unfortunately, Werkhoven and Koenderink's results could not be explained by tangential linear-speed discrimination either. If one tries to explain their results in terms of linear velocity, then the data present a systematic bias towards angular velocity. We wondered whether angular velocity was not well discriminated in their experiment, because the stimuli had few dots and thus provided poor rotational information. We retook this issue and investigated whether there are conditions under which angular velocity can be estimated more precisely.

We used the same strategy as Werkhoven and Koenderink (1993) to dissociate angular velocity from linear velocity. We performed a matching velocity experiment in which the subjects had to evaluate the speed of rotation of a test annulus with respect to a reference annulus stimulus. The perceived angular velocity was measured as a function of the ratio between the test and the reference radii ($R_t/R_r$). Stimuli consisted of quasi-random-dot-annuli revolving around a fixation mark (Barraza & Grzywacz, 2002a).

Figure 2 shows the angular-velocity-matching results of one of the naive subjects. The symbols represent the experimental data and the dotted line represents the reference angular velocity. The solid line shows the predicted angular velocity for a matching performed using tangential speeds. The data fit the reference angular velocity prediction, which means that human subjects can measure angular velocity. The systematic bias towards tangential speed...
found by Werkhoven and Koenderink (1993) did not appear in our data. Perhaps, this was because our stimulus had more dots; the mean distance between dots \( d_{\text{nd}} \) in our stimulus was 0.19°, whereas theirs was approximately 1.35°.

### 2.1 Effect of Dot Density on the Estimate of Angular Velocity

We wondered whether dot density could account for the differences between the Werkhoven-and-Koenderink's results and ours. To explore this possibility, we measured the bias in the perceived angular velocity for a wide range of \( d_{\text{nd}} \) (0.12° to 1.51°).

The bias in the perceived angular velocity (matching) is expressed as a percentage of the actual (reference) angular velocity. A bias of 100%, for example, means that the subject perceived the rotation as twice faster than the actual velocity. Because in this experiment the radius of the test was half that of the reference radius, such a bias would indicate that the subject is using the linear-velocity information to perform the task. Figure 3 shows the bias as a function of the inverse of \( d_{\text{nd}} \). Results show that, consistent with Werkhoven and Koenderink (1993), there is a bias towards tangential speed for large values of \( d_{\text{nd}} \). However, when the \( d_{\text{nd}} \) decreases, the bias falls rapidly from approximately 70% to nearby zero. In other words, when the \( d_{\text{nd}} \) is sufficiently small, subjects use angular velocity to perform the task. In contrast, for large values of \( d_{\text{nd}} \), which means poorer rotational signals, subjects use the tangential speed.

This result suggests that the brain can switch between tangential and rotational motion mechanisms depending on the density of the incoming retinal data. Interestingly, this switching is not abrupt, but there are conditions in which the perceived speed of rotation depends on tangential speed, true angular velocity, or both.

In terms of Yuille and Grzywacz's (1998) theoretical framework, this switching can be interpreted as the result of two different mechanisms competing for the parameterization of the visual motion. When the number of dots is small, the brain would not trust the signal for rotational motion and thus, the rotational model would be rejected most of the time. On the other hand, when the number of dots increases, the rotational signal would be strengthened, causing the brain to assume the motion as a rotation.
2.1.1 A Bayesian Interpretation

The schematic in Figure 4 shows graphically how the Yuille and Grzywacz framework would account for the density data. The idea is that as the density rises, the probability that a rotational model would provide a good fit would increase. To formalize the idea, we will take advantage of Bayesian Decision theory (Berger, 1985). Let $\Pi_i$ be the $i^{th}$ motion model, then, according to Bayes' theorem, the probability that a given set of $N$ velocity measurements $\{\hat{v}_m\}$ can be described by the model $\Pi_i$ is

$$P(\Pi_i|\hat{v}_m, N) = \frac{P(\hat{v}_m|\Pi_i, N) \cdot P(\Pi_i|N)}{P(\hat{v}_m|N)}$$  \hspace{1cm} (1)$$

Expanding the denominator, this equation can be written as

$$P(\Pi_i|\hat{v}_m, N) = \frac{P(\hat{v}_m|\Pi_i, N) \cdot P(\Pi_i|N)}{\sum_j P(\hat{v}_m|\Pi_j, N) \cdot P(\Pi_j|N)}$$  \hspace{1cm} (2)$$

We need to express Equation 2 for the particular case of rotation. To do this, we assume that the probabilities of other motion models, such as translation and divergence, are negligible. In other words, only the models for rotation ($\Pi_i = \Omega$) and independent ($\Pi_i = I$) motions will compete for the explanation of the stimuli. Then, Equation 2 can be written as

$$P(\Omega|\hat{v}_m, N) = \frac{P(\hat{v}_m|\Omega, N) \cdot P(\Omega|N)}{P(\hat{v}_m|\Omega, N) \cdot P(\Omega|N) + P(\hat{v}_m|I, N) \cdot P(I|N)}$$  \hspace{1cm} (3)$$

Therefore, the probability of rotation is

$$P(\Omega|\hat{v}_m, N) = \frac{P(\hat{v}_m|\Omega, N)}{P(\hat{v}_m|\Omega, N) + Ak^N},$$  \hspace{1cm} (4)$$

where $A$ is the ratio $P(I|N)/P(\Omega|N)$ and $k^N$ reflects the independence of the various $\hat{v}_m$ and that $P(\hat{v}_j) = P(\hat{v}_k)$ in our experiments, as $|\hat{v}_j| = |\hat{v}_k|$. The ratio $A$ is a parameter of the model that reflects an assumption about the statistics of natural motions. Because in our experiments, the local velocities are exactly consistent with rotation, the only reason $P(\hat{v}_m|\Omega, N) \neq 1$ is the noise in the measurement. We assume here for simplicity that this noise is Gaussian and independent across position. Therefore,

$$P(\hat{v}_m|\Omega, N) = \left( \frac{1}{2\pi\sigma^2} \right)^N \prod_{m=1}^N \exp\left( -\frac{(\hat{v}_m - \bar{u}_m(\Omega))^2}{2\sigma^2} \right)$$  \hspace{1cm} (5)$$

where $\sigma$ is the standard deviation of the noise and $\bar{u}_m(\Omega)$ is the expected measurement if there was no noise. Substituting Equation 5 for $P(\hat{v}_m|\Omega, N)$ in Equation 4 gives

$$P(\Omega|\hat{v}_m, N) = \frac{\prod_{m=1}^N \exp\left( -\frac{(\hat{v}_m - \bar{u}_m(\Omega))^2}{2\sigma^2} \right)}{\prod_{m=1}^N \exp\left( -\frac{(\hat{v}_m - \bar{u}_m(\Omega))^2}{2\sigma^2} \right) + Ah^N}$$  \hspace{1cm} (6)$$
percept is of a non-rigid rotation (Figure 6). The inner portions of the display appear to rotate much faster than the outer portions. This illusion suggests that the visual system is not using the linear velocity to evaluate the speed of rotation in the display. Presumably, the percept is that of local angular velocity, since angular velocity is inversely proportional to the distance from the center of rotation. In this case, non-rigidity would mean that the observer could perceive various angular velocities in the same object without segmenting the image. To ascertain whether this is true, we measured the perceived angular velocity as a function of the distance from the center of rotation (Barraza & Grzywacz, 2002a).

Figure 7 shows that the brain applies the rotational model locally. This figure plots the perceived angular velocity as a function of the radius of the reference disk. Symbols represent the experimental data and the solid lines represent the actual angular velocities in the annuli. Results show that the perceived angular velocity falls hyperbolically with radius and match well the actual angular-velocity prediction. Therefore, the percept of non-rigidity in this stimulus is due to the brain computing angular velocities independently at different radii of rotation. All subjects reported that the stimulus did not appear to be segmented into annuli of different radii. This is important because the interpretation of the results would be different if one thinks that the visual system is segmenting the image and integrating the measurement of angular velocity along annuli. Consequently, if there is no segmentation and the stimulus is perceived as a non-rigid object, then the brain is not computing a single global estimate of angular velocity, but appears to compute it point by point.
2.3 The Estimate of the Center of Rotation

So far, we have shown that the human visual system can estimate the angular velocity of rotational motions. Moreover, the perception of non-rigid rotations suggests that this estimate is performed locally. If this is the case, then the perception of angular velocity should depend strongly on the estimate of the center of rotation. In terms of Yuille and Grzywacz’s (1998) theoretical framework, the center of rotation is the other parameter of the model to be determined in addition to the angular velocity. We investigated whether the visual system can make precise estimates of the center of rotation. To do this, we conducted an experiment to measure the minimum distance needed for the subject to discriminate the position of the center of rotation, which was deviated from the fixation point along the diagonal of one of four quadrants in a square display. Because the center of rotation is the only point in the display where the speed is zero, we wondered whether the subject uses this particular information for the estimate. To test this hypothesis, the experiment was repeated by masking the central part of the stimulus, thereby hiding the dots falling in this area. The distance threshold was measured as a function of the radius of the mask and was obtained for two different conditions: by keeping constant either the number of dots or the density in the visible part of the display.

Figure 7. Perceived angular velocity as a function of radius in the non-rigid disk. Symbols represent the experimental data and the solid line represents the actual angular velocity along the disk. The data match well the actual angular velocities (from Barraza & Grzywacz, 2002a).

Figure 8. Position estimation of the center of rotation as a function of the mask radius. Even trained subjects cannot estimate the center of rotation precisely. Before training, errors were much higher for both subjects (black circles). Errors do not increase significantly with the radius of the mask.

Figure 8 shows that for both conditions, the subject makes an error of about 1.3° in the estimate of the center of rotation. Before training, the error was even larger (4°), as indicated by the black point in the graph. The flatness of the curves suggests that the visual system does not use the local information of the center of rotation to estimate its position, as otherwise, the error should increase significantly with the size of the mask.

What should be the effect of mislocating the center of rotation on the estimate of angular velocity? We hypothesized that when the center of rotation is deviated from the fixation point, the perceived location of the former is biased towards the latter, causing an error in the estimate of angular velocity. Because angular velocity would be computed locally, then a mislocation of the center of rotation would result in high estimates of angular velocity for those points near the perceived center of rotation. This is because velocity vectors near it would be high rather than the expected near-zero values. Therefore, in the hypothetical case that local measurements need to be integrated to give a global estimate of the motion, these errors would raise the final estimate of angular velocity. Experimental results not detailed here show that when the center of rotation is mislocated, subjects systematically overestimate the angular velocity confirming our hypothesis (Barraza & Grzywacz, 2003). This is further evidence that angular velocity is computed locally.
3 MEASURING RADIAL MOTION

That the visual system computes angular velocity is evidence that the brain uses a parametric model for rotational motion, consistent with the theoretical framework proposed by Yuille and Grzywacz (1998). This model should work in parallel with models for other types of motion such as expansion/contraction, deformation, and translation. In this section, we report that the visual system uses a parametric model for expansion as well.

Previous studies showed that human subjects can estimate the parameter named time-to-collision for simulated objects moving towards the subject or for simulated self-motions (Regan & Hamstra, 1992). One can show that for constant velocity motions, time-to-collision is the inverse of the instantaneous rate of expansion of a flow field

\[ \rho = \frac{\frac{d\theta}{dt}}{\theta} \]  

(7)

where \( \theta \) is the angular extent of the viewed object. There is no agreement yet on how the time-to-collision is computed by the visual system. One possibility is that it measures the rate of expansion instantaneously and then inverts it to compute the time-to-collision. However, a measurement of the rate of expansion cannot be exactly instantaneous, since it needs some integration time. This temporal limitation could explain the systematic errors in the estimates of time-to-collision showed in several psychophysical studies (Gray & Regan, 1999). We performed an experiment to explore whether human subjects can make precise estimates of the rate of expansion despite misestimating the time-to-collision (Wurfel, 2003). In this experiment, the motion was generated in such a way to produce a constant rate of expansion in the display. As for rotations, we controlled for the use of linear velocity by comparing expansions in disks of different radii.

Figure 9 shows that the brain also appears to use a parametric model for expansions. This figure plots the rate of expansion as a function of the ratio between test and reference radii. The symbols represent the experimental data and the dashed line, the actual rate of expansion. The solid line indicates the predicted result for the task performed by using local linear-velocity information instead of rate of expansion. The procedure used in this expansion experiment is similar to that used to measure angular velocity (Barraza & Grzywacz, 2002a). Results show that subjects can estimate precisely the rate of expansion.

Figure 9. Perceived rate of expansion as a function of Rt/Rr. The symbols represent the experimental data, the dotted line represents the rate of expansion of the reference, and the solid line represents the rate of expansion expected if the task were performed through speed matching. The results show that the subjects can measure rate of expansion in radial motions.

Is the rate of expansion computed locally as the angular velocity? If so, then the effect of non-rigidity should appear in expansions, as it does in rotational motions. In a preliminary experiment, we observed that subjects could discriminate between rigid and non-rigid expansions, reporting non-rigidity when all the dots in the display move along radial trajectories with the same speed. We also tested the effect of mislocating the focus of expansion on the perceived rate of expansion. In rotation, we found that when large random-dot fields are used, a mislocation of the focus of expansion produces a systematic overestimation of the rate of expansion. Consistently with data obtained for rotation, the overestimation reaches 20% when the deviation of the focus of expansion is about 5°. This is further evidence of a local computation of the rate of expansion as explained after Figure 8. (Interestingly, when the experiment is performed with a small expanding disk the overestimation disappears, perhaps because there is now a strong geometric clue about the position of the center of rotation.)
4 TEMPORAL COHERENCE

If some of the parametric motion models discussed so far can describe an optic flow at an instant, then it is likely that they will continue to do so for a while. This continuity follows from motion inertia in nature. Consequently, an implication of the use of parametric models by the brain is that the visual system may disambiguate, predict, and estimate motion through temporal coherence, that is, by assuming that objects move in consistent trajectories rather than abruptly changing their direction (Barraza & Grzywacz, 2002b; Burgi et al., 2000; Grzywacz et al., 1995; Ramachandran & Anstis, 1983; Verghe & McKee, 2002; Watamaniuk et al., 1995). Other motion phenomena involving temporal coherence include the improvement of velocity estimation over time (McKee et al., 1986), blur removal (Burr et al., 1986; Watamaniuk, 1992), detection of motion-outliers (Watamaniuk et al., 1995), and motion occlusion (Watamaniuk & McKee, 1995).

According to Yuille and Grzywacz's theoretical framework, temporal coherence is possible thanks to the predictions of the parametric models. Therefore, as the brain makes estimates about the future course of objects moving along linear trajectories (Verghe & McKee, 2002; Watamaniuk et al., 1995), if there is a temporal-coherence mechanism for other motion models then the brain could predict the future of the motion based on their parameters.

We tested this temporal-coherence hypothesis for rotation by exploiting the effect of mislocation of moving objects at the moment of their disappearance, such as reported by Mateeff and colleagues (1991a). These authors found a systematic location error towards where the motion was going for translational trajectories. We tested whether if one were to produce such an effect by using rotation instead of translation, then the mislocation would be consistent with the circular trajectory rather than with the instantaneous linear velocity at the time of disappearance or with a model for recent-past translation (Barraza & Grzywacz, 2002b).

We measured the perceptual location of a moving white dot (test) with respect to a static line at the moment of the luminance transition of the dot. Before the luminance transition, this dot was undergoing a clockwise rotation. The test dot was one of thirty dots arranged in an annular concentric and with the same radius as the circular motion (Figure 10a). All the dots, except for the test, were black. The white dot was set to change its luminance in one of six points on the upper portion of the annulus (Barraza & Grzywacz, 2002b). (One of these points corresponded to the top of the circle φ = 0.) Subjects mislocated this dot according to rotational temporal coherence (Figure 10b).

![Figure 10. Schematics of visual stimuli and percepts in the rotational temporal coherence experiment. Panel A shows an example of the stimulus in which the test dot (white) “disappears” at the top of the circle (φ = 0). Panel B shows schematically the subject’s percept of the location of the dot. Panel C shows the prediction of the hypothesis that the mislocation depends on the instantaneous linear velocity at the time of disappearance. The hypothesis that the mislocation depends on a translational version of temporal coherence makes an even worse prediction (Panel D).]

but not according to either the instantaneous velocity (Figure 10c) or a translational temporal-coherence assumption (Figure 10d).

We measured both the X (horizontal) and Y (vertical) perceptual locations of the dot at the time of the luminance transition as a function of the angle of luminance transition. Figure 11 shows the results of these measurements for two subjects. Results in the Y dimension (top-right plots of both panels) show that for negative angles, the test dot is perceived above its actual position (dashed line). In contrast, for zero and positive angles, the perceptual transition takes place below its actual position. These mislocations cause the data curve to be displaced to the left of the actual-positions curve. Furthermore, if one shifts the actual-positions curve leftward (by 0.14 rad), then the resulting curves fit the data well (solid line). This fit shows that subjects see the test dot disappear ahead of its actual position but in a point on its circular trajectory. As a result, the magnitude of the mislocation is not proportional to the instantaneous vertical component of velocity. (For instance, for φ = 0, despite the vertical component of velocity being zero, the dot is seen to disappear below its actual position.) Results obtained in the X dimension (bottom-left plots of both panels) are also consistent with a mislocation based on a rotational assumption. They show that the test is perceived to disappear to the right of its actual position, resulting in a downward shift of the data curve. And again, the data can be fitted well by shifting the actual positions curve downward. Importantly, these fits were obtained for both the Y and X dimensions independently, showing the same
The top-left plots in Figure 11 shows a combination of the Y and X panels. In this new panel, the perceptual location of the test dot at the time of the luminance transition in the Y dimension is plotted as a function of the perceptual location in the X dimension. This plot shows how the data produce a “rotated” circle. Therefore, subjects see the test dot change its luminance ahead of its actual position in a point belonging to the circular trajectory.

5 DECOMPOSITION OF COMPLEX MOTION

That the brain appears to use particular parametric models to interpret optic flows raises a vexing problem. Natural optic flows rarely display pure basic motion components such as translation, rotation, or expansion. Can the brain estimate the parameters of the models from motions containing a combination of more than one of these components? To answer this question, we measured the ability of human subjects to estimate either angular velocity or rate of expansion from spiral motions that is a combination of rotation and expansion. The test consisted of a matching-velocity experiment, similar to that described in Barraza & Grzywacz (2002a), but using one of the components as a mask. For instance, when the angular velocity was the parameter to be measured, the rate of expansion was the mask, varying randomly in a range defined by its variance. The distribution of the mask was homogeneous and thus, the variance indicated the maximum value that the mask component could reach. The components were measured in terms of local speeds such that a variance of 1, for example, meant that for each position in the display, the maximum speed of the radial motion was equal to the speed of the rotational motion. With this procedure, we prevented the subject from performing the matching task by using the information of the resultant vector of the spiral.

Figure 12a shows that the brain appears to solve the decomposition problem. This figure plots the ratio between matching and reference (actual) angular velocities of the rotational component of the spiral motion as a function of the variance of the radial motion (mask). (Negative values of variance apply to contraction and positive values apply to expansion.) Results show that the subject measures the correct angular velocity independently of the amount of radial motion in the spiral. This result suggests that the visual system decomposes the spiral motion in rotational and radial components. Interestingly, the slope of the psychometric functions decreases with increase of variance, which implies a rise of the threshold for angular-velocity discrimination. In Figure 12b, we plot the sensitivity for angular-velocity discrimination, the reciprocal of threshold, as a function of the variance. This sensitivity strongly depends on the amount of the mask, suggesting that

Figure 11. The two panels correspond to two different subjects, VA and JB. In each panel, the perceptual location of disappearance of the test dot as a function of the angle of disappearance for the Y dimension appears on the top-right plot. The same plot for the X dimension appears on the bottom left. Finally, the perceptual location of disappearance of the test dot in the X-Y plane appears in the top-left plot. In the X-Y plot, each perceptual location obtained in Y is plotted as a function of that obtained in X for the same angle of disappearance. Both the top-right and bottom-left plots show the data as solid diamonds, phase-shifted sinusoidal functions as solid lines, and the actual position of disappearance as dashed lines. In the X-Y panel, a circumference arc with the same radius as the annulus and concentric with it appears as a solid line. The $\Delta\phi$ angle shows the measured angular mislocation of the test (from Barraza & Grzywacz, 2002b).
Figure 12. Panel A shows the ratio between the matching and the reference angular velocities as a function of the variance of the mask. The results show that subject can estimate angular velocity when the rotation is masked with a radial motion. Panel B shows the sensitivity for discrimination of angular velocity as a function of the variance of the mask. The figure shows that there is a maximum of sensitivity when the stimulus contains no mask (pure rotation), while it decreases 50% when the variance is twice the rotational component.

although the visual system decomposes the spiral and computes the correct angular velocity, its precision falls with the increase of the mask.

How can this decomposition be instantiated? Previous studies have shown that the decomposition of spiral motions is probably not performed at the level of a single cell (Orban et al., 1992). The response of a rotation-selective cell decreases substantially when the rotational stimulus is

embedded in a radial motion. The alternate strategy would be a population-cell coding. It was found that there are cells in area MST of primates’ brain that are selective to spiral motions (Graziano et al., 1994). We hypothesize that these cells form a rotational-radial Cartesian-like space, in which the angle with respect to one of the axis indicates the proportion of rotational and radial motions in an optic flow. In turn, the distance from the origin in this space would be proportional to a cell’s optimal angular velocity and rate of expansion. In support of this notion, Graziano et al. (1994) found that spiral sensitive cells may constitute a continuum in such a space. We further hypothesize that when a particular combination of rotational and radial motions is presented, a sub-population of the cells would fire such that they agglomerate around the coordinate in this space corresponding to the stimulus. The brain may then estimate the parameters of rotational and radial motions by projecting the centers of these agglomerations onto the axes of the space.

Figure 13a shows a schematic of a hypothetic response distribution of cells in this rotation-radial space. The gray levels of the disks represent the amplitudes of the cells responses. Hence, the cell in white indicates the spiral motion to which the system is responding. Figure 13b shows, in a three-dimensional plot, a continuum of the distribution of responses to a spiral motion. The plot is truncated to illustrate the response profiles on the axes. If the response distribution is separable, then these profiles also present peaks that correspond to the component velocities, implementing the
aforementioned projection to the axes. Therefore, these profiles may encode the angular velocity and rate of expansion of the component motions of the spiral. Importantly, the height of the profile on a given axis depends on the value of the orthogonal motion component. For example, an increase of one of the components produces a reduction of this peak in the orthogonal component, without affecting the position of the peak. In turn, its reduction would produce a noisier and thus, less precise estimate of the corresponding motion parameter. This would explain why an increase of the radial component does not affect the estimated value of angular velocity, but it has a large effect on the discrimination sensitivity.

6 CONCLUSION

Humans appear to make sense of optic flows by at least in part decomposing them into a few elementary motion components. These components include translational, rotational, and radial motions. For each of the components, the brain seems to estimate their basic parameters, such as linear velocity, angular velocity, and rate of expansion. These estimates may not occur in individual cells, but rather use a population-cell code. However, the brain estimates are not always precise, with errors in the center of rotation and focus of expansion affecting the estimate of other basic parameters. The estimation of these basic parameters appears to be local and to follow a competition between the elementary motion models. If no model is sufficiently good, then the description of the optic flow is in terms of local velocity vectors, otherwise, the winner models do not only describe the instantaneous flow, but may be used to predict its future.

REFERENCES


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