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Dynamic haptics: tactile flow

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Summary. Dynamic stimuli in visual and tactile sensory modalities share fundamental psychophysical features that can be explained by similar computational models. In vision, information about relative motion between objects and the observer are mainly processed by optic flow, which is a 2D field of velocities associated with variation of brightness patterns in the image plane. It provides important information about cues for region and boundary segmentation, shape recovery, and so on. For instance, radial patterns of optic flow are often used to estimate time before contact with an approaching object. We put forward the hypothesis that a similar behavior can be present in the tactile domain, in which an analogous paradigm to optic flow might exist. Moreover, as optic flow is also invoked to explain several visual illusions, including the well-known "barber-pole" effect and Ouchi's illusion, we investigate whether similar misperceptions can be observed in the tactile domain as well. After introducing a computational model of tactile flow, which is intimately related to existing models for the visual counterpart a set of experiments aiming at reproducing the corresponding visual illusion in the tactile domain was arranged and performed. Findings of the experiments here reported indicate that visual and tactile flow share similarities at the psychophysical and computational level and may be intended for similar perceptive goals. Results of this analysis can have great impact on engineering side to implement better haptic and multimodal interfaces for human-computer interaction.

3.1 Optic flow: a brief review

Optical Flow [12] is the distribution of apparent velocities of movement of brightness patterns in an image that arises from relative motion between object and viewer or from changes in light sources. The human brain analyses this flow field to get several information from the external environment. The optic flow field contains proprioceptive, segmentation and exteroceptive information [17]. Proprioceptive information refers to both rotational and translational ego-motion and orientation. Segmentation regards splitting and merging scene zones on the basis of flow discontinuities. Exteroceptive information concern objects position, motion, form and orientation. This information is calculated by some cerebral areas [19] and, in particular, from the middle temporal area (MT), the middle superior temporal area (MST), the dorsolateral MST (MSTd) and the ventral intraparietal cortex (VIP). MT neurons are selective to direction of translation while MST neurons are selective to more complex motion patterns, such as radial, circular and spiral motions. Cells in the dorsolateral region of MST have been found to respond selectively to expansion, contractions, rotations, spirals and to multi component motions [2, 3, 10, 11, 16, 25]. Recent studies showed that other areas in the parietal lobe, such as the ventral intraparietal cortex (VIP) and area $7a$, are highly sensitive to optic flow stimuli [14]. Computational models of optic flow fruitfully contributed to the development of artificial intelligence, with a special focus on computer vision, which, in many cases, resulted, in turn, in crucial benefits to natural sciences. In particular, computational models of optic flow gained wide attention as they can predict expected outcomes of experiments and allow a deeper understanding of investigated phenomena. A widely accepted model of optic flow, proposed by Horn and Schunck [22], which mathematically describes the variation of brightness of each pixel over space and time in two sequences of a scene being moved. Hereinafter we will denote the brightness as $B(x, y, t)$. The basic idea of the model is that adjacent sets of pixels of equal intensity (iso-intensity curves), associated e.g. with objects contours, move in space through time defining a vectorial flow, that is, associating to each image point at any given instant a direction and velocity of motion. Let $v(x, y, t)$ denote the optic flow, i.e. the $2-dimensional$ velocity vector of iso-intensity curves. The optic flow equation is written (assuming that illumination changes are negligible) as

$$\frac{dB}{dt} = \frac{\partial B}{\partial x} v_x + \frac{\partial B}{\partial y} v_y + \frac{\partial B}{\partial t} = 0 \tag{3.1}$$

or, in vector notation,

$$\frac{\partial B}{\partial (x, y)} (v_x, v_y) = -\frac{\partial B}{\partial t} \tag{3.2}$$

This equation defines the optic flow vector at all image points, except for components that are tangent to the iso-intensity curve itself (i.e., components perpendicular to the spatial brightness gradient). A graphical illustration of the computational definition of flow of isointensity curves is given in Fig. 3.1.

Such an ambiguity in the constraint equation (3.1) of optic flow is often referred to as the *aperture problem*, and is crucial in generating several optical illusions. Visual information about the external environment is processed by brain through two steps [19]: firstly $V1$ (primary visual cortex) and MT calculates the local components of the flow, affected by the aperture problem; then this information is integrated and, generally, aperture problem is resolved. In some cases this cannot be done, due to a particular brightness gradient distribution or to a particular visual window. In these situations optical illusions

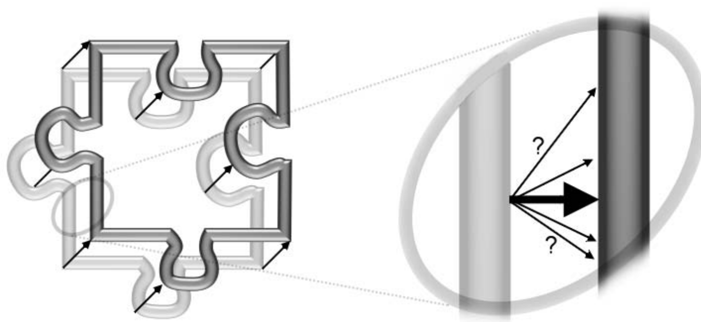

Fig. 3.1. An illustration of the concept of flow in the two-dimensional case. An iso-intensity curve of a certain level moves to a different position, defining a velocity field. However, having all points on the same curve the same intensity, it is not possible to distinguish their pair wise correspondence. This leaves the tangential component of velocities undefined, and gives raise to the so-called *aperture problem*, which in turn may generate perceptual illusions.

based on optic flow can arise. The problem is irrelevant for punctual features (e.g., corners), for which the flow is uniquely defined. Punctual features are indeed used by our perceptual system to disambiguate illusory cues. Barber Pole Optic Illusion [20] is just a direct consequence of the aperture problem in the optical flow neural analysis. Barber Pole Illusion refers to the optic effect which results from the horizontal rotation of a vertical pole, on which there are diagonally oriented decorative strips. During rotation, the observer has the sensation the strips are moving upwards, while they are actually horizontally moving. This illusion can be explained by the fact that, being the motion of a linear pattern observed through a small window which prevents any distinctive feature to be perceived, then no cue is available indicating whether or not motion occurred along the pattern direction.

3.2 From optic flow to tactile flow

3.2.1 Comparison between coding system used by visual and tactile modalities

Even though the sense of touch may seem very different from sight, there exist many similarities between them. When exploring the surrounding environment touch and vision usually work together in a highly cooperative manner during the manipulation, apprehension and identification of objects. This cooperation is at the basis of the nature of multimodal perception and intersensory integration [13].

Vision is most often used to identify objects, although the tactile system is also useful. Haptics can provide information about the weight, compliance, and temperature of an object, as well as information about its surface features such as how sticky or slippery it is, information that is not readily available by merely looking at the object. However, even though haptics and vision both provide information about an object's volumetric shape, the modality of interaction is quite different. The receptor surfaces of both systems have regions of low and high acuity. For vision, the high-acuity region of the retina is the fovea; for haptics, the high-acuity regions are the fingers, lips, and tongue.

Physiologically, receptors codifying the images (cones and rods) are located at level of the retina. The neural coding of the visual information is conveyed from the retina to the *Lateral Geniculate Nucleus* (LGN) and the scene is analysed and vectorially split by means of the Ganglion Cells into many components, termed channels [5]. These channels are responsible for codifying relevant features of the image such as color, contrast and brightness. A first neural parallelism between touch and vision can be found by comparing the properties of the channels relating to hue, saturation of colour and intensity of light, to channels lying in the skin which give information about intensity of pressure, change of pressure and temperature. On the contrary, while skin uses many separate receptors to perceive different stimuli, the eye relies just on the rods and cones and the information is obtained through analysis. Nevertheless, since the code system used by the mechanoreceptors is still under investigation, the hypothesis that skin uses a similar analytical mechanism cannot firmly excluded. In addition, in the LNG there exists additional complex cells which use a tree-like structure analysis of the image to detect the presence of edges and objects moving in a given direction, as well as the spatial frequency of the stimulus. A similar pattern also exists in the haptic mechanism of perception. Another analogy is based on the lateral inhibition analysis. In haptic perception it was experimentally shown that monkeys and man both exhibit lateral inhibition to increase sensory acuity, i.e. some receptive fields on the skin are linked to Ganglion Cells in such a way that they respond to a specific stimulus. This mechanism also exists in the visual system. For example, an object of a specific size may stimulate a separate single channel. A strict analogy can be also found between the stimulus of contrast codified by the eye and the contrasts in pressure codified by the haptic modality [23]. Moreover, many similarities in neural coding between the two senses appear evident in the several experiments performed on blind people. Through brain-mapping techniques of investigation, it was found that when a blind person is given a touch stimulus, the pathways to visual cortex are activated as well as the normal pathways. If a normal person with eyes closed performs the same task, the visual cortex does not display such activity. This means that in blind people the touch sense provides surrogating sensations for the sight. This confirms that information in both senses are codified in similar way.

3.2.2 The new paradigm: tactile flow

Our hypothesis is that there might exist a tactile concept similar to optic flow. In a previous work [1] authors have proposed a new psychophysical hypothesis to convey haptic information. In particular it has been conjectured that a large part of haptic information necessary to discriminate softness of objects by touch is contained in the law that relates resultant contact force to the overall area of contact, or in other terms in the rate by which the contact area spreads over the finger surface as the finger is increasingly pressed on the object.

This new conjecture takes inspiration from the time to contact paradigm in the vision field. Time to contact is one application of optical flow, sometimes pessimistically referred to as time to collision or time to crash. Usually, when an object positioned at distance D from a camera moves with constant velocity v towards it, it will crash at time τ, called time to collision, $\tau = D/v$. If the relative motion occurs along the line of sight, i.e. the camera is translating but not rotating, and the environment is static, the flow field has a simple radial form (see Fig. 3.2). The center of the radial flow pattern is called Focus of Expansion (FoE). FoE gives the direction of motion in the visual frame of reference. In other words, the image of an approaching object expands. In this case, only using optical measurements based on the optic flow and without knowing the velocity or distance from the surface it is possible to determine when the crash will occur. By processing the optic flow by means of suitable algorithms it is possible to infer the time to collision. In particular, it is sufficient to pick a point in the image and divide its distance from the FoE by its divergence from the FoE. An alternative viewpoint is to define the time to contact as the ratio between the visual angle between a point on the image and the FoE and the rate of change of this angle. Important implications of time to contact are in driving and avoiding collision, flying and landing and sports (boxing, football, baseball, ...). In the time to contact paradigm the iso-brightness contours move towards radial direction and the change rate of area comprised between two contours after a lapse of time is calculated as

$$\frac{dA}{dt} = \oint_{c(t)} \vec{\Phi} \cdot \vec{n}\, dl = \int\int_{A} \nabla \cdot \vec{\Phi}\, dA$$

where $\vec{\Phi}$ is the optic flow vector, $\vec{n}$ is the local versor perpendicular to contour.

It is noticeable a good resemblance between the growing rate of the contact area between the finger pad and an object during a tactile indentation task and the convergence or divergence of the vision field in time to contact task. In particular, the divergence from FoE of optic flow represents the expansion of iso-brightness contours. The area delimited by a closed iso-brightness contour grows with motion over time likewise the growth of the contact area in the tactile domain. This analogy led us to define a new conjecture, inspired to optic flow, which we called *tactile flow*.

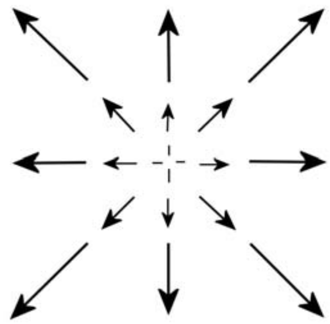

Fig. 3.2. Distribution of optic flow of an image moving forward.

The counterpart of iso-brightness curves in the tactile domain could be chosen between stress and strain profiles. Some evidence of this choice can be found by a psychophysical viewpoint. For instance, [7] shows that tactile information for stimuli increasing at a fixed rate, is more reliably conveyed when the stimulus is skin indentation rather than force intensity. In a similar spirit, experiments have been performed on mechanoreceptors in the racoon [15]. A likely analogy, hence, can be recognized between the divergence from FoE of optic flow and the spread of contact area superficial iso-strain profiles, which are concentric circles with center at the initial contact point, in the case of solids of revolution, during a mechanical interaction between two bodies. By analogy to iso-brightness curves in optic flow it is more convenient to manage a scalar rather than a tensor such as strain. A scalar strictly related to strain tensor is Strain Energy Density (SDE).

SDE is mathematically expressed by

$$U_{strain} = \sum C_{m,n} \varepsilon_n \varepsilon_m \tag{3.3}$$

where C is the stiffness tensor, and ε are components of the strain tensor. In analogy to the optic flow, we can define a 2D scalar field

$$U_{strain}(x, y, t) \tag{3.4}$$

Considering a contact between a pattern and a fingertip, the SDE at a particular point in the pattern changes spatially and with time. For small indentations we can assume that the spatial gradient of SDE is compensated by the time variation, such that the total differential remains unchanged. Hence, we can write

$$\frac{dU_{strain}(x, y, t)}{dt} = 0 \tag{3.5}$$

and expanding the above equation we obtain

$$\frac{\delta x}{\delta t} \cdot \frac{\partial U_{strain}}{\partial x} + \frac{\delta y}{\delta t} \cdot \frac{\partial U_{strain}}{\partial y} + \frac{\partial U_{strain}}{\partial t} = 0 \tag{3.6}$$

Even in this case, in analogy to the optic flow, the above equation can be called "tactile constraint equation", and it is affected by the tactile aperture problem as well. Experiments afterwards described are performed to verify the existence in the tactile domain of similar illusions to that related to the aperture problem of the optic flow.

When the fingerpad squeezes an object, by within the contact area it is possible to identify curves of iso-SDE. As the contact area spreads, the curves moves as well. We can associate to the contact area spread rate the flow of the iso-SDE curves.

We can define as tactile image a given iso-SDE curve. During a small indentation, tactile image moves to another one, generating an expansion or a contraction of the iso-SDE contours. The variation of the area comprised between two iso-SDE can be expressed as

$$\frac{dA_c}{dt} = \oint_{c(t)} \overrightarrow{\varphi} \cdot \overrightarrow{n}\, dl = \int\int_{A_c} \nabla \cdot \overrightarrow{\varphi}\, dA$$

where φ is the tactile flow, i.e. the velocity vector of the SDE.

Tactile flow, hence, can be associated to the Contact Area Spread Rate (CASR) paradigm. Indeed, we can assert that information codified by tactile flow is the compliance (softness perception) and it can be used to develop new haptic technologies.

3.3 Experiments

Several experiments were planned to be performed in order to support the conjecture of the existence of an analogous paradigm of optic flow in the tactile domain. As it is well known, optic flow is affected by an intrinsic ambiguity, called *aperture problem*, which generates several illusions. We arranged a set of experiments aiming at verifying whether in the tactile domain similar illusions might exist.

3.3.1 Barber pole illusion

Participants

41 right-handed and healthy participants (17 females and 24 males) volunteered to participate in the experiment. Their age ranged from 23 to 42 years (average 29 years). All participants were naïve to the purpose of the experiment, and gave informed consent to participate.

Apparatus and Stimuli

The experimental apparatus to reproduce the Barber Pole Illusion (aperture problem) in tactile form (depicted in Fig. 3.3) consisted in a linear motorized slide with changing orientation, onto which a textured pad can be fixed at different angles. The pad is realized in aluminum, and presents a series of 1-mm high, 1-mm wide ridges separated by 1-cm wide grooves. An opening

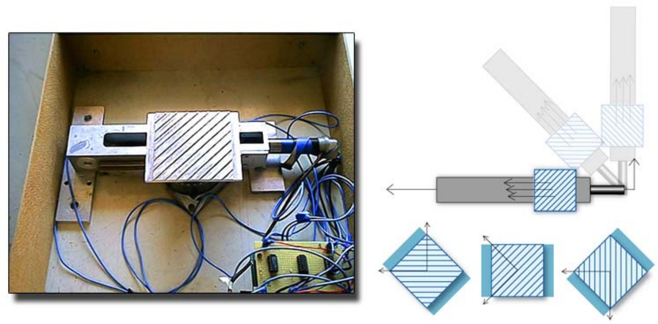

Fig. 3.3. Experimental apparatus used for the tactile Barber pole experiment:top view on the left and slide/pad orientation on the right

of about the size of a human forefinger was made on the cover, so as to allow contact of the subject's finger with the pad. The experiment consisted in keeping the finger still, while the pad was moved slowly by the slide in a direction unknown to the subject, while being fixed on the slide at an angle also unknown. A small curtain was used to prevent subjects from seeing the pad motion. In different subsequent tests, the direction of motion of the slide was set to 0 degrees (motion perpendicular to the subject's finger), 45, and 90 degrees (motion aligned with the finger). For each orientation of the slide, the pad texture could be placed at different angles, ranging from 0 to 150 degrees, relative to the fingertip.

Design and Procedure

In this experiment, a liquid soap was used as a lubricant between the finger and the pad, so as to limit skin stretching due to friction between the finger and the pad. Each subject was asked to determine if any motion was perceived and, if so, to describe the motion direction. Different directions were reported on the cover, and labeled with numbers from 1 to 24, visible to subjects. Answers such as "between direction 3 and 4" were interpreted as 3.5 (resulting in a resolution of 7.5 degrees). Each subject (Fig. 3.4) was presented with 24 different combinations of three slide directions (at 0, 45, and 90 degrees) and 8 texture orientations (at 0, 30, 45, 60, 90, 120, 135, and 150 degrees) in random order, for a grand total of 1128 trials. Before making a decision, a subject could ask for repetitions of the task.

Fig. 3.4. Volunteer during an experimental test.

Results and Discussion

Experimental results are reported in Fig. 3.5, plotting the angle between the perceived and actual direction of motion (on the vertical axis) versus the angle between the direction of motion of the pad and the orientation of texture (horizontal axis). It can be observed that the discrepancy between the actual and

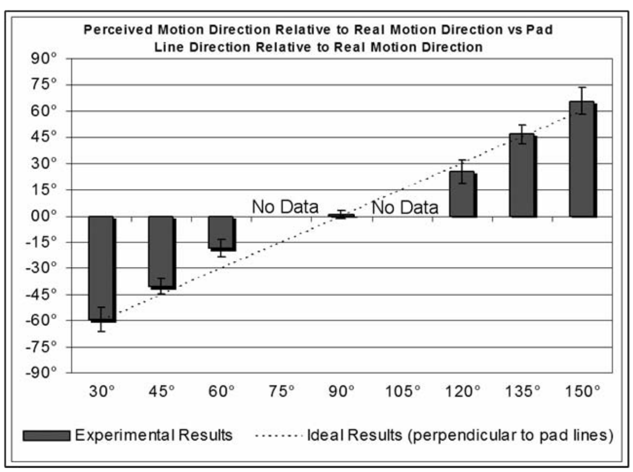

Fig. 3.5. Results of the tactile barber pole experiment. The dashed line indicates a perfectly illusory response.

perceived direction of motion increases almost linearly with the texture slant.

A dashed line is also reported for reference, corresponding to the theoretical case that the perceived direction is always perpendicular to the texture, independently of the actual direction of motion. Such an ideal case, corresponding to a perfectly illusory motion, is what is typically obtained with the optical barber pole illusion. In experiments where the texture was aligned with the slide motion, no illusion is to be expected, consistently with the optical illusion counterpart. Indeed, in this case, 65% of the subjects reported that there was no motion at all (which is again the expected answer in the analogous visual experiment), while 35% reported an approximately correct direction of motion (no illusory response). For consistency's sake, these data have not been reported in the graph of Fig. 3.5.

A two-way ANOVA analysis to explore the interactions between perceived directions with slide motions (sessions) or pad orientations (blocks) revealed that grating inclination of the pad (hence tactile flow) was significantly relevant to motion perception ($F_{(7,14)} = 846.76, \alpha = 0.05, p < 0.0001$), while no statistical evidence of a role of the actual direction of motion was found ($F_{(2,14)} = 1.17, \alpha = 0.05, p = 0.34$).

3.3.2 Multifinger Tactile Barber Pole illusion

This experiment was conceived to show how two tactile stimuli, acting on two different fingertips so as to generate incoherent barber-pole illusions, are instead integrated by the human brain, thus overcoming the illusion.

Participants

20 subjects (12 females, 8 males) volunteered to participate in the experiments. Their ages ranged from 25 to 31 years, with an average of 28.1, with a university degree and normal health conditions. All participants were naïve of the purposes of the experiment.

Apparatus and stimuli

Experiments were conducted by stimulating the subjects fingertips, held fixed by a supporting jig, by pressing and sliding pads with different relief patterns. Both the contact pressure and the sliding motions were accurately controlled through a mechanisms for 3D motion generation (a Delta Haptic Device (DHD) by Force Dimension), which allowed us to apply suitable forces to fingertips and record frictions. The DHD was oriented so as to move horizontally and placed near a fixed mechanical structure, or jig, in which two openings of about the size of a human forefinger were used to hold the subjects fingers comfortably fixed, supporting them against pressure exerted by the moving pad fixed to the DHD (Fig. 3.6). The device and the pads were hidden to subjects view by a curtain. The pad was realized by 3D printing in

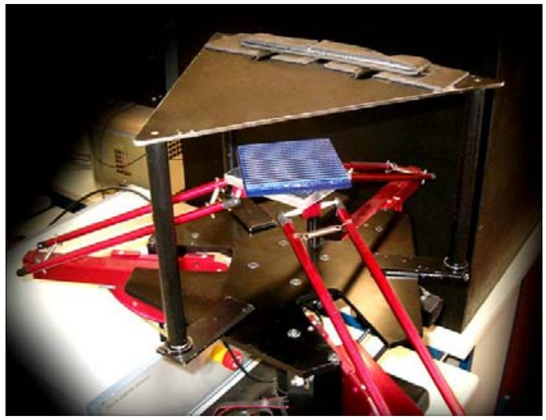

Fig. 3.6. Mechanical structure used in the experiments, composed by a DHD and a fixed supporting structure for the hands.

nylon. It presents a series of $1mm$ high, $3mm$ wide parallel ridges separated by $5mm$ grooves. Contours are smoothed with a fillet radius of $0.25mm$. The pad was realized with two similar patterns, differing only by their inclination (Fig. 3.7). The inclination of the ridges of the pad relatively to the actual

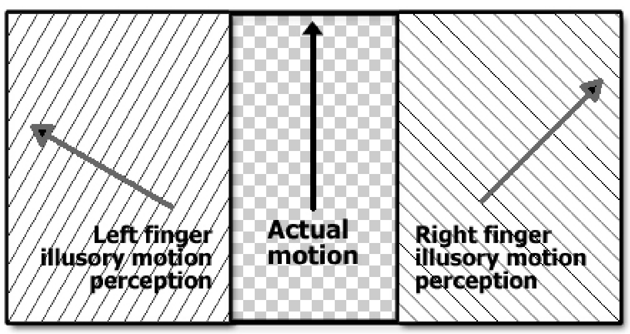

Fig. 3.7. Pad used in first experiment. The inclination of the ridges of the pad relatively to the actual motion direction was of -30 degrees in the left side of the pad and 45 degrees in the right side of it.

motion direction was of -30 degrees on the left side of the pad and 45 degrees on the right.

Design and Procedure

The experiment consisted of slowly moving the pad by the DHD, while keeping the finger still. After each movement of the pad, subjects were asked to report on the perceived motion direction. We used soap as lubricant to reduce friction between fingertips and pads. In each trial, the DHD is controlled so as to initially put the pad in contact with the fingertip of subjects with a perpendicular force of $0.3N$. Afterwards, upon instructions of the assistant, a straight sagittal motion of the pad of length $8cm$ at a velocity of $0.7cm/s$ is imposed by the DHD. Such an operation induces an approximately sinusoidal mechanical excitation of the fingertip, with a characteristic amplitude (related to the height of the ridges) and frequency (about $0.87Hz$). The amplitude was chosen so as to stimulate SA1 cells just below their saturation level, while frequency was designed to stimulate principally Merkel cells (which best respond in a bandwidth between $0.3Hz$ to $3Hz$). The use of the lubricant was introduced to avoid skin stretching, thus effectively inhibiting the response of Ruffini corpuscles [8]. In the first test a forefinger of the left hand was stimulated by the pattern on the left side of the pad depicted in Fig. 3.7. Secondly, the forefinger of the right hand was treated analogously with the pattern on the right. Thirdly, both subjects forefingers were placed in contact with the respective side of the moving pad. Two trials were made in each of these phases, after each of which subjects were asked about the perceived direction of motion. A control test was finally conducted using a pad without a preferential pattern, covered by sandpaper, designed to remove any flow-related illusory stimulation.

Results and discussion

Experimental results are reported in Fig. 3.8, plotting the angle representing the average perceived direction of motion in the three phases of the experiment. It can be noticed that in the tests in which subjects used just one

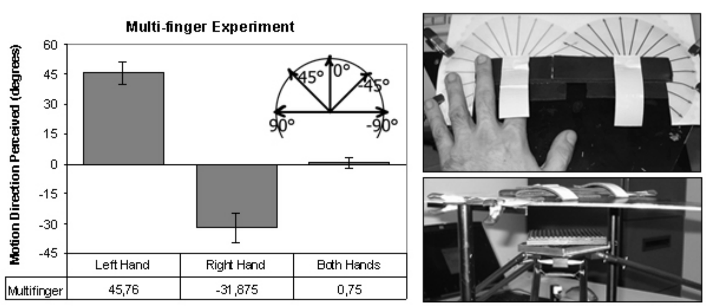

Fig. 3.8. Experiment results. Left: average perceived angles of motion in the three phases. Right: experimental setup.

forefinger, the direction of motion consistently perceived by subjects is perpendicular to the ridges in the pattern, in accordance to the tactile barber pole illusion discussed above. When using both hands, however, subjects consistently reported a perceived motion in the sagittal direction. In the control test with the pattern-less pad all subjects correctly detected the direction of motion. In an ANOVA analysis of significance, three treatments are considered corresponding to the use of the right hand, the left hand, and both hands. The (null) hypothesis that differences between experimental results with the left and right fingers alone may not be statistically significant, has negligible probability, thus confirming prior results indicating a strong relevance of flow-induced tactile illusions. We can also affirm, with negligible doubt margin, that results of the two-finger experiment are completely uncorrelated with those of either right- or left-finger alone. On the contrary, results from the multi-finger test are congruent with the control test with a p-value of 0.7 (70%). Also for this experiment, results are very similar to those obtained with the optical version of the illusion and can be explained in terms of brain elaboration of tactile and optic flow, as can be found below in this document.

3.3.3 The role of friction in the barber pole illusion

Participants

The same 20 subjects (12 females, 8 males) as the previous experiment volunteered to participate also in this experiment, whose purpose was hidden to them.

Apparatus and stimuli

A suitable hardware setup similar to that used in the first experiment (Delta Haptic Device (DHD) by Force Dimension) was also used in this experiment. The experiment consisted of two parts, in which the same mechanical apparatus as the multifinger barber pole illusion was used and a pattern-bearing pad was moved in a similar way. However, no lubricants is used in this test, which were intended to study the effects on tactile perception of coupling normal and tangential forces on the skin, and just one forefinger was used by subjects.

Design and Procedure

The experiment is subdivided into two parts. In the first part, four pads of different materials were employed, presenting a pattern of ridges inclined relatively to the actual motion direction by -45 degrees. The four pads were realized in rubber, plastic, cardboard, and sandpaper, respectively, offering an increasing feeling of friction to sliding. The second part of the experiment was arranged so as to isolate the role of tangential forces from that of different materials. A single nylon pad was employed with a pattern of $1mm$ high, $3mm$

wide parallel ridges separated by $3mm$ grooves, with fillet radius of $0.5mm$, inclined relatively to the actual motion direction by -45 degrees. In different runs of the test, however, different pressures of the pad against the fingertip were commanded, of $0.3N$, $0.8N$, $1.3N$, $1.8N$, $2.3N$, and $2.8N$. In each trial, tangential forces arising by the imposed motion of the pad have been measured and logged.

Results and discussion

Experimental results of the first part of the experiment are reported in Fig. 3.9, showing that an increasing macroscopic friction progressively reduces the illusory effect of moving ridges, so that using the sandpaper pad the actual motion is clearly perceived by subjects, while using the others pads an illusion can be perceived.

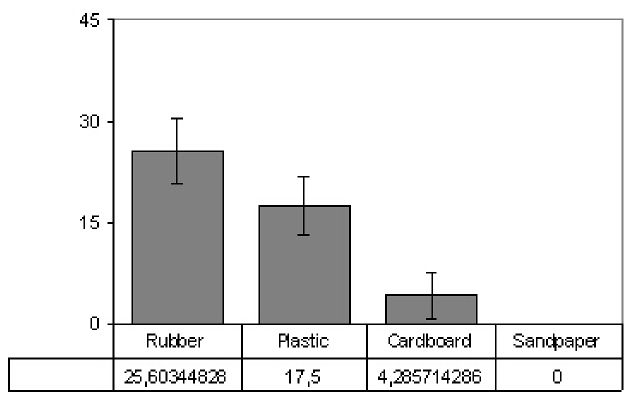

Fig. 3.9. Perceived motion direction versus different pad materials.

Experimental results of the second part of the experiment are reported in Fig. 3.10. It can be observed that, for tests where the pad was pressed against the fingertip less heavily, the perceived direction of motion is strongly influenced by the aperture problem, notwithstanding the higher friction coefficient. For higher values of compression, however, subjects responded mostly with a correct perception of the direction of motion. It should be pointed out that higher compression, with constant coefficient of friction, effectively implies a larger tangential stretch on the fingertips skin. In an ANOVA statistical study of significance of data for this experiment, six treatments are considered corresponding to different normal forces. The (null) hypothesis that differences between each treatment and the next one are not statistically significant ranged between a p-level of 0.0262 (normal forces of $0.3N$ and $0.8N$) and a p-level of

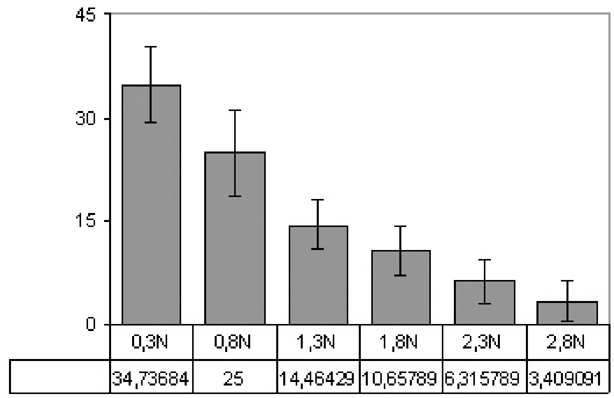

Fig. 3.10. Perceived motion direction versus normal force.

0.1825 (normal forces of $2.3N$ and $2.8N$), indicating that differences between normal forces are statistically significant in the experiment results. A very interesting finding in this second phase is that 55% of subjects, for compression forces in the range between $0.8N$ and $1.3N$ (corresponding to tangential forces between $0.4N$ and $0.6N$), reported feeling a clockwise rotation of the pad. This illusory motion has been called tactile vertigo. In all such subjects, an increment of normal force stopped the vertigo inducing subjects to perceive the actual direction of motion, while a decrease of the normal force induced alignment to the barber-pole illusory direction. The graph in Fig. 3.11 reports the probability to perceive the vertigo in function of the friction between pad and finger during translation.

3.3.4 Tactile Ouchi Illusion

Participants

20 subjects (9 females, 11 males) volunteered to participate in this experiment. All participants were naïve of the purposes of the experiment. All subjects (all right handed) used their right hand forefinger to touch the pad.

Apparatus and stimuli

The goal of this experiment was to replicate and study the Ouchi optic illusion in the tactile domain. The Ouchis visual pattern reported on the left side of Fig. 3.12 has the propriety that small relative motions between the pattern and the eyes cause illusory perception of a partition of the inset from the background region. The effect can be achieved either with small retinal motions or a slight jiggling of the paper and is rather robust over large changes in pattern,

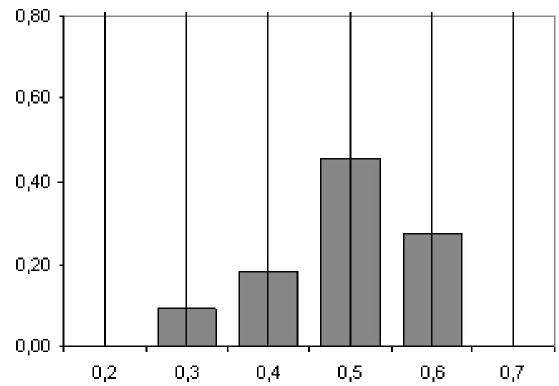

Fig. 3.11. Probability to perceive the vertigo versus friction between pad and fingertip.

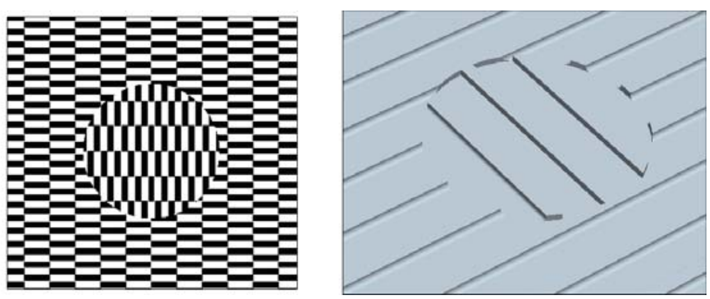

Fig. 3.12. The Ouchi Pattern (left) and its simplified version (right) used in the experiment.

frequencies and boundary shapes. A possible explanation is that the illusion is caused by a segmentation of the optic flow field due to a biased estimation of local optic flow components [9]. Actually, the estimation of image velocity is generally biased, and for particular spatial gradient distribution similar to the Ouchi pattern the bias is particularly pronounced, giving rise to large differences in the velocity estimates between the inner and the outer zone of pattern. A simplified 3D model of the Ouchis pattern was realized by means a technique of microprinting in a nylon structure. This pattern was placed on the end-effector of the Delta Haptic Device (DHD) which was suitably controlled via PC. The pad was moved beneath a metallic plane endowed with a small opening through which subjects could put their forefinger and touch the moving pad. The motion imposed on the pad was a vibration in random direction of $4Hz$ with $2mm$ of amplitude. This frequency was chosen in order to maximize the response of Meissner corpuscles, partially elicit the Merkel receptors and quelling the remaining mechanoreceptors.

Design and Procedure

The group of volunteers was asked to touch the pad and report on what they perceive. Results are discussed, interpreted and compared with those of the more known optic illusion. In our experiment, the pad should vibrate according to certain specifications. In particular, the oscillation frequency should be comprised within a predetermined range and the amplitude of vibration should be quite small. In order to attain these requirements with sufficient reliability, as in the above experiments, we used the Delta Haptic Device (DHD) by Force Dimension. The idea of using this commercial device is justified by the observation that some kinaesthetic parameters, such as position and velocity, can be dynamically estimated during the tactile manipulation while other parameters, such as forces along desired axes, can be timely fixed without compromising realism (the parameters' values are always coherent) and performance. However, the aim of our experiment was only to induce a vibration without imposing forces. The frequency and amplitude of vibrations were verified a posteriori by reading the output of the position sensor integrated in the device. We realized a simplified version of the Ouchi pattern Fig. 3.12 (on the right side) with size comparable to fingertips dimensions. The pad was realized by means of 3D printing on a structure of nylon. It presents a series of $1mm$ high, $1mm$ wide parallel ridges separated by $2mm$ grooves, and the contours are smoothed with a curvature radius of $0.2mm$. Ridges in the inset are orthogonally inclined with respect to the ridges in background. Lubricant was used on both fingertip and pad. This pad was placed on the end-effector of the DHD combined to a fixed mechanical structure in which one opening of about the size of a human forefinger was used to allow subjects to put their right forefinger. The device and the pad were hidden to subjects view by a curtain. The DHD was programmed to vibrate with frequency of $4Hz$ and $2mm$ of amplitude in random direction; the DHDs push-button allowed us to remove the vibration at the end of the experiment. Each subject kept still the finger while the pad is vibrating as long as he likes. After experimenting he was asked to freely describe the tactile perception without any suggestions.

Results and discussion

45% of subjects reported feeling an illusory perception. Among these, a subgroup of subjects $(66,6\%)$ perceived a segmented texture, in which the inner circle was felt raised against the surrounding area, and the remaining volunteers $(33,3\%)$ received the complementary perception. However, in both situations a different depth between the inner circle and the surrounding area was perceived. These results well agreed with the visual Ouchis illusion and could be explained in terms of segmentation of the tactile flow consequent to a different local bias. The oscillation of 4 Hz involves mainly the Meissner corpuscles, more sensitive to vibrations, but partially elicits also the Merkel disks. In this way the two categories of mechanoreceptors, i.e. Merkel and Meissner corpuscles, judged to play an important role in the tactile flow are both addressed. The low percentage of subjects reporting the illusion has been probably caused by the poor tactile resolution and contrast compared to the resolution of the optic system, therefore only the most sensitive subjects (largely female subjects in our tests) perceived an illusion. In literature a number of works can be found on the optic version of the Ouchi illusion, aimed at understanding how different parameters of the patter may influence illusion perception. Khang and Essock [9] performed experiments with a number of variations of the original pattern to evaluate the impact of various parameters, such as orientation and size of the pattern elements, luminance and blurring. They found that a sinusoidal waveform instead of the rectangular one or a blurred version of the pattern strongly reduce the magnitude of the illusory relative motion and of the segmentation effect. In Fig. 3.13 and Fig. 3.14 two versions of the Ouchi pattern can be observed with an increasing blur effect, which presents a decreasing magnitude of illusion. We performed a trivial optic test to understand the importance of the optic focus and contrast on illusion perception. Indeed, in the optic version of illusion, short-sighted subjects taking off their glasses reported a decrease of the effect (tests independently performed on different subjects). Moreover, we would like to stress that, while almost in all experiments performed in literature subjects reported to perceive a relative motion between inset and background regions, a percentage of them reported an apparent depth discontinuity [18].

3.3.5 Integral Tactile Flow (ITF) and discrimination of softness

The literature on haptic discrimination of softness (e.g. [4, 16]) has clarified that human capabilities in this task depend strongly on cutaneuous information, being Haptic Illusions induced by Tactile Flow proprioceptive perception are relatively awkward at this. However, it has later been argued that a significant part of the haptic information used to discriminate softness does not actually rely on detailed sensing of the stress-strain distribution in the skin at and near the contact, rather it is strongly related to how fast the contact area grows when the probing force is increased. This relationship, which bears some resemblance to the information on the velocity of an approaching object (or time-to-contact [24]) conveyed by the increase in size of its retinal image, was formalized in the concept of Integral Tactile Flow (ITF) paradigm, as explained above in the tactile flow paragraph, and validated by means of several psychophysical experiments in [1], in which the ITF paradigm is explained in terms of Contact Area Spread Rate (CASR). In one of those experiments, 15 volunteers were asked to recognize 5 different items by touch only. Their performance in the recognition task was compared when they were touching the original specimens, or two artificial replicae. Results of these experiments,

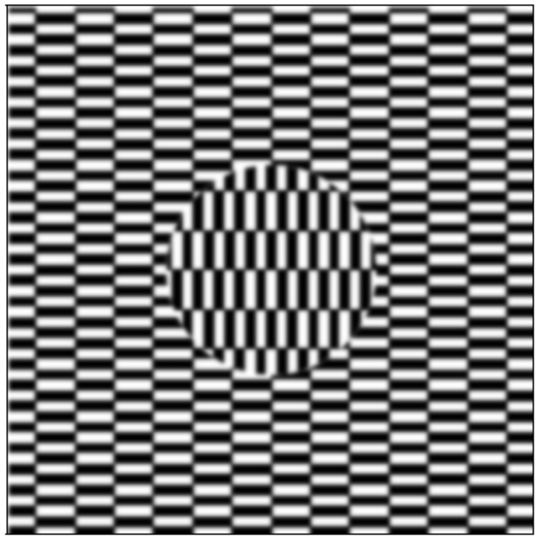

Fig. 3.13. A blurred version of the Ouchi pattern.

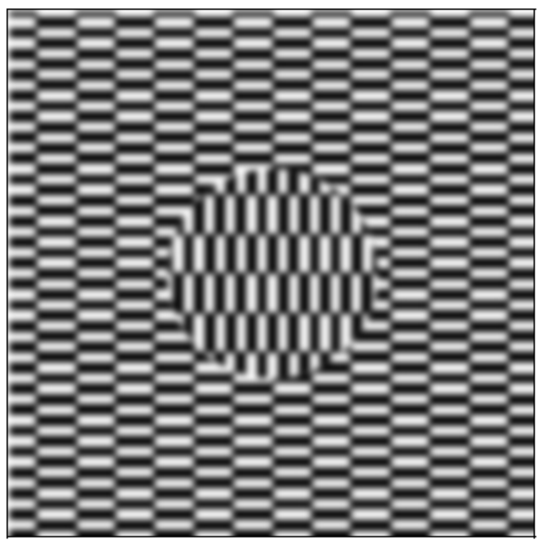

Fig. 3.14. A more blurred version of the Ouchi pattern.

described in detail in [1], are reported in Fig. 3.15 for reference, and show how CASR is indeed extremely useful in our perception of softness by touch.

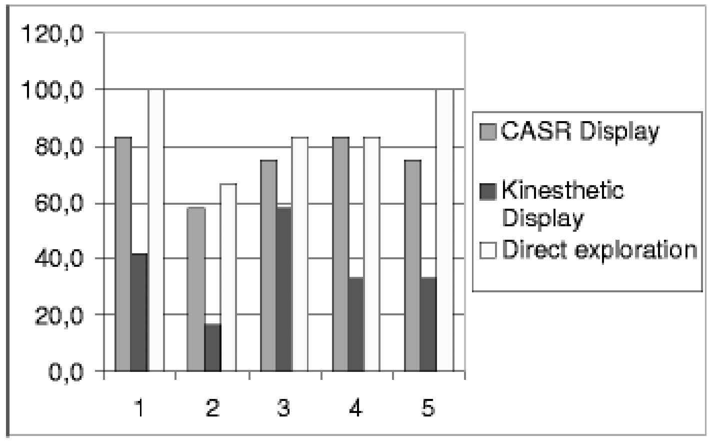

Fig. 3.15. Percentage of successful recognition of 5 specimens of different softness by direct exploration, and by exploration of two artificial replicae of their proprioceptive and CASR behaviours, respectively.

3.4 Conclusion

Results from tactile barber pole illusion, as well as the other experiments, can be explained in terms of the aperture problem of the tactile flow elaboration by the brain. As an isointensity curve of a certain level moves to a different position, defining a velocity field, having all the points on the same curve the same intensity, it is not possible to distinguish their pairwise correspondence. This makes the tangential component of velocities undefined, and gives rise to the tactile illusion. Results from the experiments here reported can be explained in terms of brain elaboration of tactile and optic flow. Computational models and biological tests indicate that optic flow may be derived in a two-stage process [9, 17], and that different brain zones accomplish this two-stage process [6, 19]. According to this model, flow components perpendicular to linear features are computed first from local image measurements. Such a computation is affected by the aperture problem [22]. In a second stage these local components are integrated into the actual motion perception. In the barber pole illusion all the local flow components are parallel, so that integration of these components does not overcome the aperture problem. Looking at a moving rectangle we can understand its actual motion only if we can see the motion of two non parallel contours, or a corner. The multifinger barber pole experiment indicates that a similar behavior can be proposed for tactile flow integration. While indeed perception from each single finger is not sufficient to perceive the actual motion, the integration of local information from both forefingers allows subjects to estimate it coherently.

In the experiment aiming at investigating the role of friction in the barber pole illusion, the perceived motion direction appears to be a weighted sum (integration) of the illusory motion with the real one, with weights strongly related to the intensity of skin stretching forces. An explanation of this phenomenon can be given in terms of the different relative level of excitation of afferents in the skin under the described experimental conditions. Indeed, while excitation of mechanoreceptors sensitive to strain energy density (i.e., Merkel Cells and Meissner corpuscles [21]) is saturated throughout the experiments, receptors responsive to skin stretching (SA2 or Ruffini corpuscles) are more strongly stimulated in tests where a higher tangential force was adopted. According to the computational model of tactile flow proposed, Merkel and Meissner corpuscles are extremely sensitive to tactile flow, while Ruffini corpuscles perceive magnitude and direction of skin stretching, which is always directed towards the actual motion. Increasing the magnitude of friction the discharge rate by SA2 afferents increase, letting subjects better perceive the actual motion, while the saturation of Merkel cells leaves the illusory stimulus provided by the moving oblique ridges almost unaltered. The tactile vertigo arises with friction forces between $0.4N$ and $0.6N$. Probably in these circumstances the strength of the two different stimuli is comparable so that subjects cannot decide how to integrate the discordant. An anomalous motion integration therefore appears, transmitting the sensation of a rotating pad to the subjects. As for the experiment of Ouchi illusion, the single tile used to make up the pattern is four times longer than it is wide, and this implies a gradient distribution in a small region with four times as many normal flow measurements in one direction as the other. This difference in gradient distributions leads to a biased perception in different directions of the optic flow when it is estimated from local measurements. In particular the perceived pattern motion direction was biased towards the direction perpendicular to the orientation of the grating with higher frequencies [26]. A similar experiment was performed in the tactile domain. A simplified 3D pattern inspired to the Ouchi grating was realized of nylon. It is worthwhile noting the difficulty of implementing a pad with a detailed texture having the size of a forefinger. The lack of high spatial resolution, indeed, impinged on the performance of the experiment. In order to replicate the illusion in tactile terms, the only solution was to make the pad vibrate at a suitable frequency. Moreover, since the aim of the experiment was to mainly elicit the mechanoreceptor deemed to play a relevant role in the tactile flow mechanism, we have chosen a vibration frequency of the pad of 4 Hz. This frequency actually falls within the bandwidth of Meissner corpuscles (which best respond in the range of 3-40 Hz), being responsible for sensing vibrations, but it is also the upper frequency cut-off of the Merkel receptors which, in addition to a pretty good response to dynamical stimuli, has a better spatial resolution. Taking into account the hurdles to perform the experiment, results are very similar to the optic version of the illusion. In conclusion, all experiments here described aimed at investigating the possibility that a tactile concept similar to optic flow might exist. Moreover, looking at results from experiments, we can also hypothesize that a supramodality of flow analysis may exist. Results from the Integral Tactile flow experiment show that the integral version of the tactile flow is strictly related to the Contact Area Spread Rate paradigm, hence to softness discrimination. This last important finding can be profitably exploited for implementing new high performance haptic displays.

3.5 Acknowledgments

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References

1. Bicchi A, De Rossi D, and Scilingo E P (2000) IEEE T Robotic Autom, 16(5):496–504.
2. Orban G A, Lagae L, Verri A, Raiguel S, Xiao D, Maes H, and Torre V (1992) Proc Natl Acad Sci USA, 2595–2599.
3. Saito H A, Yukie M, Tanaka K, Hikosaka K, Fukada Y, and Iwai E (1986) J Neurosi, 6(1):145–157.
4. Srinivasan M A and LaMotte R H (1995) J Neurophysiol, 73(1):88–101.
5. Goldstein E B (2002) Sensation and Perception.
6. Morrone M C, Tosetti M, Montanaro D, Fiorentini A, Cioni G, and Burr D C (2000) Nat Nuerosci 3(12):1322–1328.
7. Greenspan J D (1984) Somatosens Res 2(1):33-48.
8. Vega Bermudez F and Johnson K O (1999)J Neurophysiol 81:2701–2710.
9. Khang B G and Essock E A (1997) Perception 26(5):585–597.
10. Duffy C J and Wurtz R H (1991) J Neurofisiol 65(6):1329-45.
11. Duffy C J and Wurtz R H (1991) J Neurofisiol 65: 1346-1359.
12. Gibson J J (1950) The perception of the visual world. Houghton Mifflin, Boston.
13. Lederman S J and Browse R A (1988) The physiology and psychophysics of touch. In: Sensors and Sensory Systms for Advanced Robots. Springer-Verlag, New York.
14. Schaafsma S J, Duysens J, and Gielen C (1997) Vis Neurosci 14(4):633–646.
15. Pubols B H Jr and Pubols L M (1982) Brain Res 233(2):409–413.
16. Tanaka K, Fukada Y, and Saito H A (1989) J Neurosci, 62:642–656.

17. Barron J L, Fleet D J, and Beauchemin S S (1994) Int J Comput Vision 12(1):43–77.
18. Spillmann L, Tulunay-Keesey U, and Olson J (1993) Invest Ophth Vis Sci 34:1031.
19. Vaina L M (1998) Curr Opin Neurobiol 8(4):494–502.
20. Fisher N and Zanker J M (2001) Perception 30(11):1321–1336.
21. Johnson K O, Yoshioka T, and Vega Bermudez F (2000) J Clin Neurophysiol 17(6):539-558.
22. Horn B K P and Schunck B G (1981) ARTIF INTELL, 17:185–203.
23. Whittle P (1998) Haptic perceptionas part of NST IB Experimental Psychology lecture handouts, University of Cambridge.
24. Cipolla R and Blake A (1997) Int J Robot Res 16:77–96.
25. Graziano M S, Andersen R A, and Snowden R (1994) J. Neurosci 14:54-67.
26. Smith A T and Edgar G K (1991) J Opt Soc Am 8(7):1161–1171.