Integration of Tactile Flow from Multi-Finger and Multi-Dimensional Information

Davide Dente, Andrea Pisani, Enzo Pasquale Scilingo, Antonio Bicchi

Pisa TouchLab
Interdepartmental Research Center "E. Piaggio", Università di Pisa
Via Diotisalvi 2 – 56100 Pisa – Italy - Web: www.piaggio.ccii.unipi.it
Email: {davide.dente, e.scilingo, bicchi}@ing.unipi.it

Abstract. In this paper we pursue an investigation on the role of perceptual flow in the tactile domain, which appears to be a primary source for information such as shape, motion and softness. In this paper, we report on a set of psychophysical experiments involving how humans integrate incoherent tactile flow stimuli. Two experiments are reported, whereby discordant stimuli are conveyed to the subject by two different fingertips, or by two different families of mechanoreceptors in the same finger. Results from the first experiment show that, in these conditions, the tactile and the optic perceptive systems act in a very similar way. In the second experiment the interaction between tactile flow and friction generate an illusory phenomenon peculiar of the tactile system.

1 INTRODUCTION

Various similarities exist between vision and touch. In the field of visual perception, studies on *optic flow* have played an important role in the developments of the science of vision in humans and in computer vision technology. In our previous work, we advanced the hypothesis that there may exist a tactile counterpart to optic flow, called tactile flow, whose role would include gathering information not only about relative motion, but also an object's shape and softness.

In a previous work, Bicchi et al. (2003) [2] showed the possibility to reproduce in tactile form some well known optic illusions related to flow. The tactile "barber pole" illusion [4] refers to the analogous optical effect resulting when an upward motion of diagonal strips is falsely induced from the actual rotational motion of a striped pole. This effect is due to the well known *aperture problem* (see [2]) in the elaboration of local optic flow components, whereof only flow components along the brightness gradient are elicited. The tactile barber pole experiment reported in [2] showed that, when a pad with a series of parallel ridges and negligible friction is moved along a given direction, subjects are unable to detect the actual direction of motion, and an illusory motion along a direction normal to the ridges is perceived. To push the analogy with optic flow further, we investigate here whether the brain is able to integrate two stimuli, which would separately cause such illusions, into a correct perception.

We report on a psychophysical experiment 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.

A peculiarity of tactile perception with respect to vision is the deeply different nature and functions of receptors. In a human fingertip, the mechanoreceptors mediating the motion direction perception can be divided into two main groups: receptors sensitive to strain energy density, hence to skin deformation (i.e., Merkel Cells and Meissner corpuscles) [6], and receptors responsive to skin stretching (Ruffini corpuscles). The first group results to be more sensitive to dynamic stimuli, while the latter has significant steady-state sensitivity. Being perceptual flow an eminently dynamic phenomenon, it is to be expected that it should be mostly mediated by the former group of receptors (Pacini corpuscles have extremely poor localization properties, hence their role in flow should be discounted as well). Our second experiment is intended to investigate subjective perceptions when the two groups of receptors are stimulated with varying relative intensity, and elucidate how their perceptual information are integrated in these conditions.

2 PSYCHOPHYSICAL EXPERIMENTS – METHODS

20 subjects (12 females, 8 males) volunteered to participate to 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. All subjects participated to all experiments.

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 ForceDimension), which allowed us to apply suitable forces to fingertips and record frictions.

Different conditions of lubrication between sliding pads and subjects' fingertips were used in tests, as described below, so as to modify the tangential force distribution in the skin, allowing differential excitation of different tactile afferents.

### 2.1 Experiment 1 – Multifinger tactile barber pole

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 subject's fingers comfortably fixed, supporting them against pressure exerted by the moving pad fixed to the DHD (fig. 1).

The device and the pads were hidden to subjects' view by a curtain. The pad was realized by 3D printing in 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.
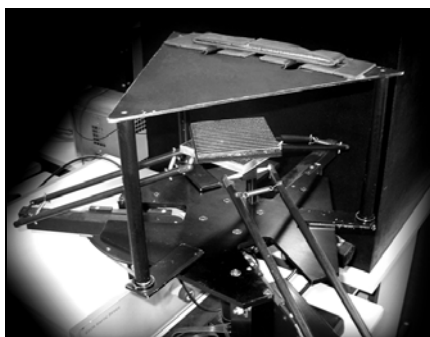
Fig. 1 - Mechanical structure used in the experiments, composed by a DHD and a fixed supporting structure for the hands.

The pad was realized with two similar patterns, differing only by their inclination (fig.2). The inclination of the ridges of the pad relatively to the actual motion direction was of -30 degrees on the left side of the pad and 45 degrees on the right.
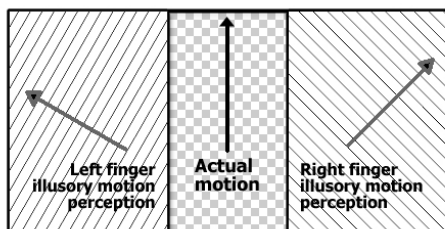
Fig. 2. Pad used in first experiment. The inclination of the ridges of the pad relatively to the actual motion direction was of -30 degrees in the left side of the pad and 45 degrees in the right side of it.

The experiment consisted in 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, at a command 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 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 [9].

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.2. Secondly, the forefinger of the right hand was treated analogously with the pattern on the right. Thirdly, both subject's 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.

Experimental results are reported in fig. 3, 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 forefinger, the direction of motion consistently perceived by subjects is perpendicular to ridges in the pattern, in accordance to the "tactile barber pole" illusion discussed in [2]. 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%).
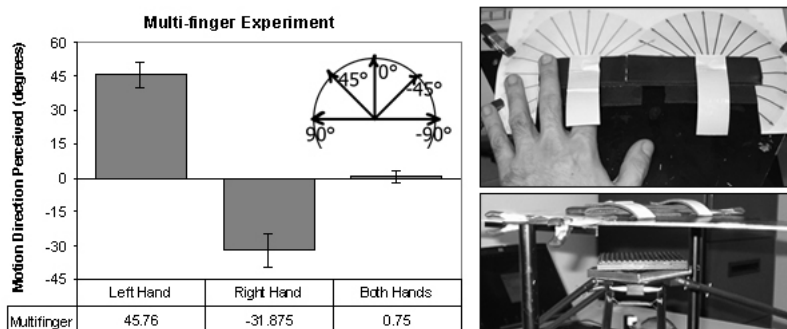
Fig. 3. First experiment results. Left: average perceived angles of motion in the three phases. Right: experimental setup.

2.2 Experiment 2 – Integration of multi-dimensional force stimuli

The experiment consisted of two parts, in which the same mechanical apparatus was used as described for the first experiment and a pattern-bearing pad was moved in a similar way. However, no lubricants were used in these tests, which were intended to study the effects on tactile perception of coupling normal and tangential forces on the skin.
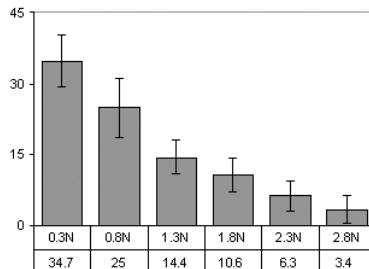
In the first part of the experiment, four pads of different materials were employed, presenting a pattern of ridges inclined relatively to the actual motion direction by -45 degrees. The four pads were realized in rubber, plastic, cardboard, and sandpaper, respectively, offering an increasing feeling of friction to sliding.

Experimental results are reported in fig.4, showing that an increasing macroscopic friction progressively reduce 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.

The second part of the experiment was devised 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. Experimental results are reported in fig.5. 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 fingertip's skin.

	Rubber	Plastic	Cardboard	Sandpaper
	25.6	17.5	4.2	0
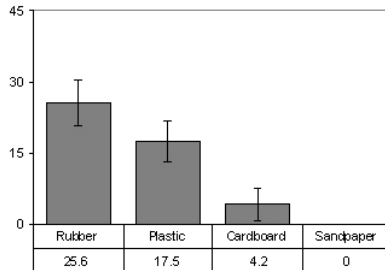
Fig. 4. Perceived motion direction versus different pad materials.

	0.3N	0.8N	1.3N	1.8N	2.3N	2.8N
	34.7	25	14.4	10.6	6.3	3.4

Fig. 5. Perceived motion direction versus normal force.

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 signifi-cant ranged between a p-level of 0.0262 (normal forces of 0.3N and 0.8N) and a p-level of 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 com-pression 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 is consistent with occasional findings reported in [2], and 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.6 reports the probability to perceive the vertigo in function of the friction be-tween pad and finger during translation.
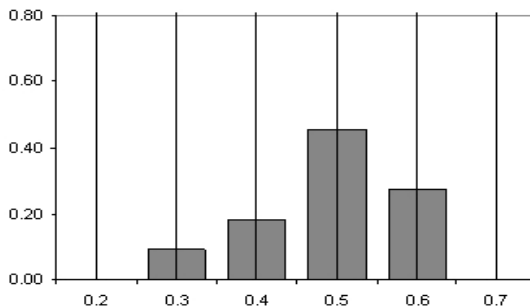

Fig. 6. Probability to perceive the *vertigo* versus friction between pad and fingertip.

3   DISCUSSION

Results from the first experiment 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 [1][10], and that different brain zones accomplish this two-stage process [7][8]. According to this model, flow components perpendicular to linear features are computed first from local image measurements. Such computation is affected by the aperture problem [5]. 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 compo-nents 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 con-tours, or a corner.

The first experiment reported in this paper indicates that a similar behaviour 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 second experiment the perceived motion direction appears to be a weighted sum (integration) of the illusory motion with the real one, with weighs strongly related to 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 [6]) 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 in [2], Merkel and Meissner corpuscles are extremely sensitive to tactile flow, while Ruffini corpuscles perceive magnitude and direction of skin stretch, 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 hence appear, transmitting to subjects the sensation of a rotating pad.

5 Conclusions

In this paper we illustrated behaviours in tactile perception that bear a strong resemblance to observations made concerning optic flow elaboration by the human brain. The peculiarities of the tactile system related to the vision however also generates previously unexpected situations, without a direct visual counterpart.

The reported experiments strongly support the notion that touch is an eminently dynamic sense, and that tactile flow is probably one of the main sources of tactile information. Observations made in this paper are considered very relevant to the design of the next generation of tactile displays, where the dynamic nature of touch could be addressed by developing interfaces that reproduce shapes and contours not just statically, but also exploiting dynamic features.

6 Acknowledgement

7 REFERENCES

1. Adelson E. H., Movshon J. A.: Phenomenal coherence of moving visual patterns. Nature, 300, (1982) 523-525
2. Bicchi A., Dente D., Scilingo P.: Haptic Illusions induced by Tactile Flow. Conference Proceeding, EuroHaptics (2003) 314-329
3. Fermüller C., Pless R., Aloimonos Y.: The Ouchi illusion as an artifact of biased flow estimation. *Vision Research*, 40 (2000) 77-96
4. Fisher N., Zanker J. M.: The directional tuning of the barber-pole illusion. Perception (2001), volume 30, n.11, 1321-1336
5. Horn B. K. P., Schunck B. G.: Determining Optical Flow. AI 17 (1981): 185-203
6. Johnson K. O., Yoshioka T., Vega Bermudez F.: Tactile functions of mechanoreceptive afferents innervating the hand. J Clin Neurophysiol (2000) 17: 538-558
7. Morrone M. C., Tosetti M., Monatanaro D., Fiorentini A., Cioni G., Burr D. C.: A cortical area that responds specifically to optic flow, revealed by fMRI. Nature Neuroscience, Vol. 3 (2000) 12: 1322-1328
8. Vaina L. M.: Complex motion perception and its deficits. Current Opinion in Neurobiology (1998) 8: 494-502
9. Vega Bermudez F., Johnson K. O.: SA1 and RA receptive fields, response variability and population responses mapped with a probe array. J Neurophysiol (1999) 81: 2701-2710
10. Welch L.: The perception of moving plaids reveals two motion-processing stages. Nature, 337 (1989) 735-737