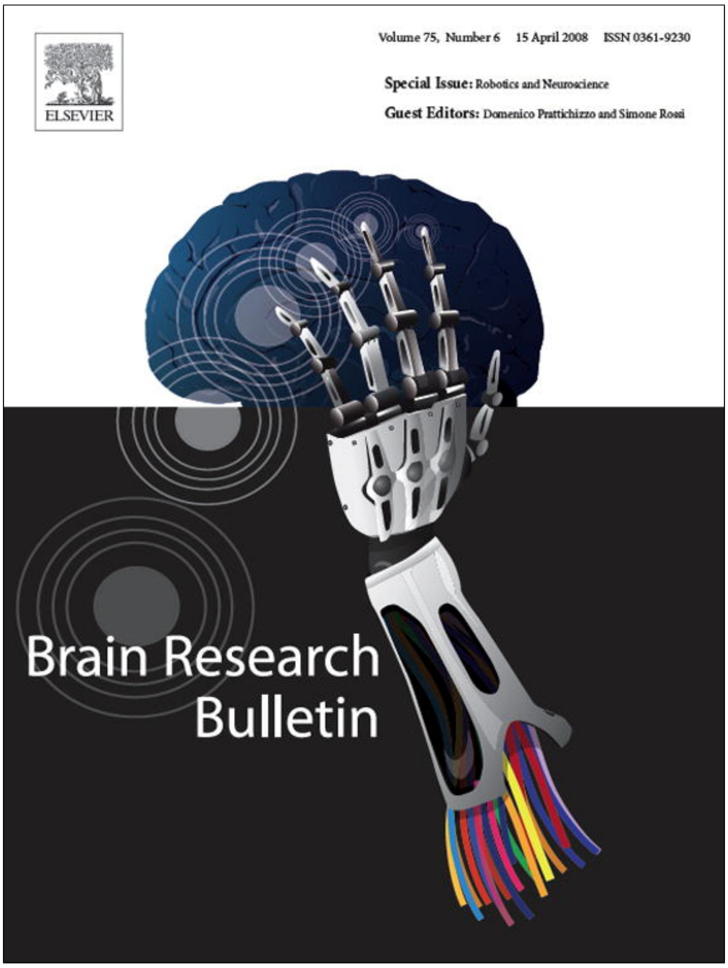
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Research report

Tactile flow explains haptic counterparts of common visual illusions

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Abstract

Interaction with the external world requires the ability to perceive dynamic changes in complex sensorial input and react promptly. Here, we show that perception of dynamic stimuli in the visual and tactile sensory modalities share fundamental psychophysical aspects that can be explained by similar computational models. In vision, optic flow provides information on relative motion between the individual and the content of percept. For instance, radial patterns of optic flow are used to estimate time before contact with an approaching object [J.J. Gibson, What gives rise to the perception of motion? Psychol. Rev. 75 (1968) 335–346]. Similarly, in the tactile modality, radial patterns of stimuli provide information on softness of probed objects [A. Bicchi, D. De Rossi, E.P. Scilingo, The role of the contact area spread rate (CASR) in haptic discrimination of softness, IEEE Trans. Rob. Autom. 16 (2000) 496–504]. Optic flow is also invoked to explain several visual illusions, including the well-known "barber-pole" effect [N. Fisher, J.M. Zanker, The directional tuning of the barber-pole illusion, Perception 30 (2001) 1321–1336]. Here, we introduce a computational model of tactile flow, which is intimately related to existing models for the visual counterpart. The model accounts for psychophysical aspects of dynamic tactile perception and predicts illusory phenomena in the tactile domain, analogous to the barber-pole effect. When subjects touched translating pads with differently oriented gratings, they perceived a direction of motion that was significantly biased towards the orientation of the gratings. Therefore, these findings 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 have impact on the engineering of better haptic and multimodal interfaces for human–computer interaction.

Keywords: Optic flow; Tactile flow; Haptic illusions; Mechanoreceptors

1. Introduction

While exploring the surrounding environment, we usually deal with dynamic sensorial inputs, arriving from different spatial sources. The ability to enrich our percept with those additional information supplied by in-time and in-space changeable stimuli is critical for interacting more efficiently with the external world. For instance, visual motion perception hints also on spatial depth or object shape recognition, as well as on direction of heading and spatial self-orientation [8,9]. In this case, the continuously varying visual stimulation on the retina has been psychophysically conceptualized in the optic flow model [8,9].

Since various physiological and functional similarities exist between visual and tactile perception, and both modalities cooperate to get an unified percept of the explored world [2,6], we hypothesized that a tactile counterpart of optic flow, referred to as *tactile flow*, might exist and share similar psychophysical properties. Tactile flow would gather information not only about softness discrimination and relative motion between fingertip and surface in contact, but would also assist in object shape recognition and segmentation.

To substantiate such hypothesis, we conceptualize the flow invariants in the tactile domain through a suitable model, by adapting Horn and Schunck's model of optic flow [13]. In that model, motions of visual patterns in an image sequence are subjected to constraints, which are described by means of a partial differential equation involving the spatial coordinates of the image plane (denoted by vector x), time (t), and the intensity $B(x,t)$ of a physiologically relevant parameter in the image, e.g.

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brightness, as

$$\frac{\partial B}{\partial x}\vec{\phi}(x,t)+\frac{\partial B}{\partial t}=0. \tag{1}$$

Here, $\vec{\phi}(x,t)$ denotes the flow of adjacent sets of pixels of equal intensity (iso-intensity curves, associated with contours of objects). The constraint Eq. (1) defines the flow vector $\vec{\phi}(x,t)$ for each point of the image, except for those components that are tangent to the iso-intensity curve itself (i.e., components perpendicular to the intensity gradient). The incomplete definition of flow is normally overcome by integrating the information obtained by flow of non-parallel contours attributed to the same object. However, when such cues are not available (as, e.g. when looking through a small aperture), the ambiguity of tangent flow components originates several optical illusions, among which the well-known barber-pole illusion [7], discussed below.

In tactile perception, the stimulation of mechanoreceptors depends upon a rather complicated distribution of mechanical stresses and strains in the skin, represented by three-dimensional tensorial fields [7]. The tactile flow model we propose here consists of a formally identical expression as Eq. (1), with the difference that the variable x in this case denotes the spatial coordinates of a volume element in the fingertip tissue, and $B(x,t)$ indicates the intensity of the tactile stimulus in x at time t. Data from psychophysical and neurophysiologic studies of touch [15,16] indicate that the Strain Energy Density (SED) – or other closely related components of tissue strain – can be used as the perceptual intensity $B(x,t)$ which "flows" in tactile perception. Indeed, the Merkel-SA1 afferents, which are primarily responsible for dynamic form and texture perception in tactile scanning, are selectively sensitive to SED.

This tactile flow model provides an explanation for previously published experimental findings [3]. The ability to discriminate softness, for which cutaneous information is crucial [26], depends to a large extent on perception of the rate at which the contact area spreads over the fingertip surface when the probing force is increased [3]. This so-called contact area spread rate (CASR) phenomenon recalls the relationship between the rate of dilatation of the retinal image of an approaching object and the estimate of relative velocity of motion, as observed in time-to-contact experiments [5,12]. Time-to-contact appraisal is considered a manifestation of the ability of visual perception to detect invariants of the dynamic optic array, in particular its optic flow [8,9]. Recognizing that most of the cutaneous information involved in softness discrimination by probing is conveyed by a simple force–area relation, enabled useful technological developments, for instance in the construction of simpler and more effective haptic displays for human–computer interaction [3].

The points on the fingertip surface where tissues are exposed to equal strain energy density (hence similar stimulation of SA1 afferents) form iso-SED contours. During softness discrimination, tactile images vary and generate expansions or contractions of the iso-SED surfaces. The larger the total probing force, the farther a surface corresponding to a given level of SED is from the center of the contact zone. An increasing probing force F causes iso-SED surfaces to flow outwards radially relatively to the center of contact, and as a consequence the area of the fingertip surface involved in contact is dilated. The rate of such dilatation is a direct function of tactile flow, which can be evaluated mathematically as

$$\frac{\mathrm{d}A_c}{\mathrm{d}F}=\oint_c \vec{\phi}\cdot\vec{n}\,\mathrm{d}l=\iint_{A_c}\nabla\cdot\vec{\phi}\,\mathrm{d}A \tag{2}$$

where A_c is the area comprised by the iso-SED contour c, $\vec{\phi}\cdot\vec{n}$ is the SED flow vector projected along the normal direction to the contour, and $\nabla\cdot\vec{\phi}$ the divergence of the flow. Of note, formula (2) is analogous to the optic flow computational model of time-to-contact [5]. The stress–strain distribution in the fingertip, hence tactile flow, depends clearly on the rheological characteristics of the contacted object, differing largely, e.g. for soft and stiff objects, and for elastic or viscous materials. The information on tactile flow from cutaneous SA1 afferents is consequently sufficient to support softness discrimination [3].

Eq. (1) allows for infinite solutions. This ambiguity provides an explanation for the barber-pole illusion [7] in the visual domain. This consists in the non-veridical perception of the direction of motion of translating gratings. When observed from a small aperture, allowing perception only in the vicinity of a contour, motion is perceived in the direction perpendicular to the contour, irrespective of the actual motion direction.

According to the proposed tactile flow model, a similar illusory effect can be predicted in the tactile domain. Therefore, in the current study we designed an experiment to determine whether and how the tactile perception of motion is influenced by the actual direction of movement, and by different grating textures on the surface of the moving object. Our adapted model for tactile flow predicts that texture orientation will prevail when local cues only are perceived, and therefore significantly bias perception of direction.

2. Materials and methods

Subjects were instructed to touch with their right forefinger tip a lubricated pad with a pattern of parallel ridges and grooves, slowly moved by a slide, and to report the perceived direction. The pad was fixed on the slide at a specific angle. Both slide directions and pad angles were unknown to subjects. Experimental tests were organized in three sessions in which the direction of the slide motion was varied (0°, 45° and 90°). Each session consisted of eight blocks, corresponding to the pad being fixed at different angles with respect to the finger (0°, 30°, 45°, 60°, 90°, 120°, 135°, and 150°).

The experimental apparatus consisted of a linear motorized slide with variable orientation, onto which a textured pad was fixed at different angles. The pad was realized in aluminum, and presented a series of 1-mm high, 1-mm wide ridges separated by 1-cm wide grooves. An opaque box contained the slide and pad, with on opening of about the size of a human forefinger in the upper side. A small curtain was used to prevent subjects from seeing the pad motion and orientation.

The pad was lubricated by liquid soap and put in contact with the right forefinger tip of 41 healthy volunteers (mean age = 29 yrs, range 23–42 yrs; 24M/17F). All participants were naïve of the purposes of the experiment, and gave informed consent to participate. The pad was moved in different directions by a motorized linear slide. Subjects held their forefinger still on the texture, and were asked to report on the perceived direction of motion by referring to a radial grid of 24 lines 15° apart (see Fig. 1). Answers such as "between direction 3 and 4" were interpreted as 3.5.

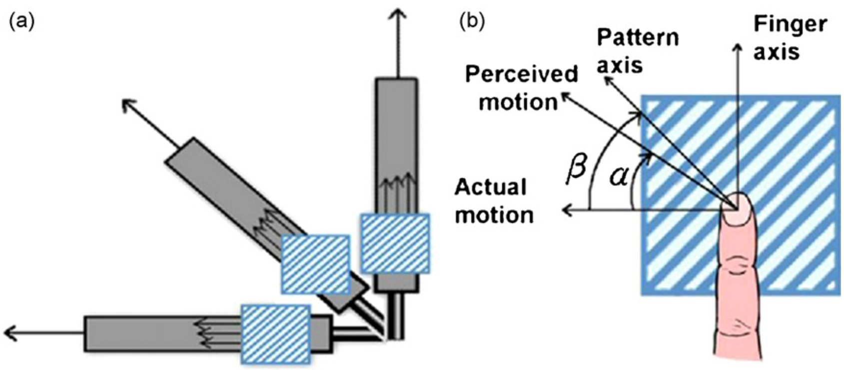

Fig. 1. The apparatus for the tactile barber-pole experiment. (a) Textured pad mounted on a motorized slide moving towards three different directions. (b) The angle α is between the perceived and actual directions of motion (on the vertical axis) while the angle β is between the actual direction of motion and the axis of the pattern on the pad for three different motion directions.

In separate consecutive tests, the direction of motion of the slide was set to 0° (motion perpendicular to the subject's finger), 45°, and 90° (motion aligned with the finger). For each orientation of the slide, the pad texture was placed in different trials at angles of 0°, 30°, 45°, 60°, 90°, 120°, 135°, and 150° relative to the fingertip, respectively. Each subject was presented with 24 different combinations of three slide directions and 8 texture orientations for a grand total of 1008 trials. Orientations and directions were randomized across subjects. Before making a decision, a subject could ask to repeat the trial. Data from those trials where the pad was translating in a direction parallel to the ridges were not included in the group analysis.

A two-way ANOVA test was used to evaluate the across-subjects interactions between perceived directions with slide motions (sessions) or pad orientations (blocks). A linear regression was assessed on experimental data, and tested against a theoretical slope, as predicted by our tactile flow equation.

3. Results and discussion

Experimental results for each slide motion are presented in Fig. 2. 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, $p = 0.34$).

Fig. 2D reports experimental results from all the trials performed. In all plots relative angular coordinates were used. In these coordinates, veridical data would lie on the horizontal axis, while perfectly illusory perceptions (as predicted by the tactile flow model) would lie on a straight line of unitary slope (dashed red in figure) and intercept at 0°. The linear fit to experimental data (solid black line $R^2 = 0.98$, slope 0.96 ± 0.01, intercept $-3.27 \pm 0.96°$) did not significantly differ from the correlation slope predicted by the tactile flow model ($t_{(821,0.95)} = -0.72$; $p = 0.47$).

These experimental data do not rule out a role of the actual direction of motion on subjective perception. In fact, during those trials with $\beta = 0$, where the pad was translated perpendicularly to the ridges (i.e., when the tactile flow cue was consistent with the actual motion direction), percepts were the most consistent across subjects and trials ($\sigma \approx 2°$). To better understand the role of the actual direction of motion on tactile perception, we designed additional experiments where we minimized the flow of SED. In a first experiment, the pad was translated in a direction parallel to the ridges. In this case the fingertip deformation levels were equivalent to those in the previous experiments but SED distribution did not vary in time, and therefore did not convey any flow cue. Results showed that 38 out of 41 participants could not perceive any motion.

In a second experiment, we replaced the ridges with a random pattern of slightly protruding asperities, which resulted in a time-varying SED but of smaller amplitude. Subjects perceived the direction of motion with no significant illusory bias, but with a large response variability ($\sigma \approx 23°$), much greater than that generally observed in the first set of experiments in which tactile flow cues were not attenuated (σ ranging between 2 and 16). In conclusion, tactile flow cues provide more coherent perception than that provided by actual motion per se, though they are prone to illusions in particular cases.

A possible explanation of the influence of actual motion on perception is related with kinesthetic cues elicited by finger stretching, due for instance to SA2-Ruffini and Golgi organs. Lubrication of the sliding pad was included in the experimental protocol to reduce friction and hence kinesthetic interference with cutaneous information.

As a result of our experiments, psychophysical and computational evidence support the existence of deep analogies between flow in the tactile and visual perceptual domains. Specifically, we demonstrated the existence of a *tactile flow* that shares similar psychophysical properties with the optic counterpart. Furthermore, our experimental findings validated tactile flow more extensively may gather information not only about relative motion and pressure between the fingertip and the surface in contact, but also on softness discrimination and object shape recognition.

The similarities between the information about the external world provided by the two different perceptual channels [2,6] lends ground to the hypothesis that both optic and tactile flow are processed by the same cerebral areas, likely the early regions of the dorsal "visual" pathway responsive to visual motion perception, such as the human MT complex (hMT+). Consistently with previous physiological knowledge, brain functional studies showed that human visual MT complex exhibits consistent responses to perception or imagery of moving stimuli, but also to

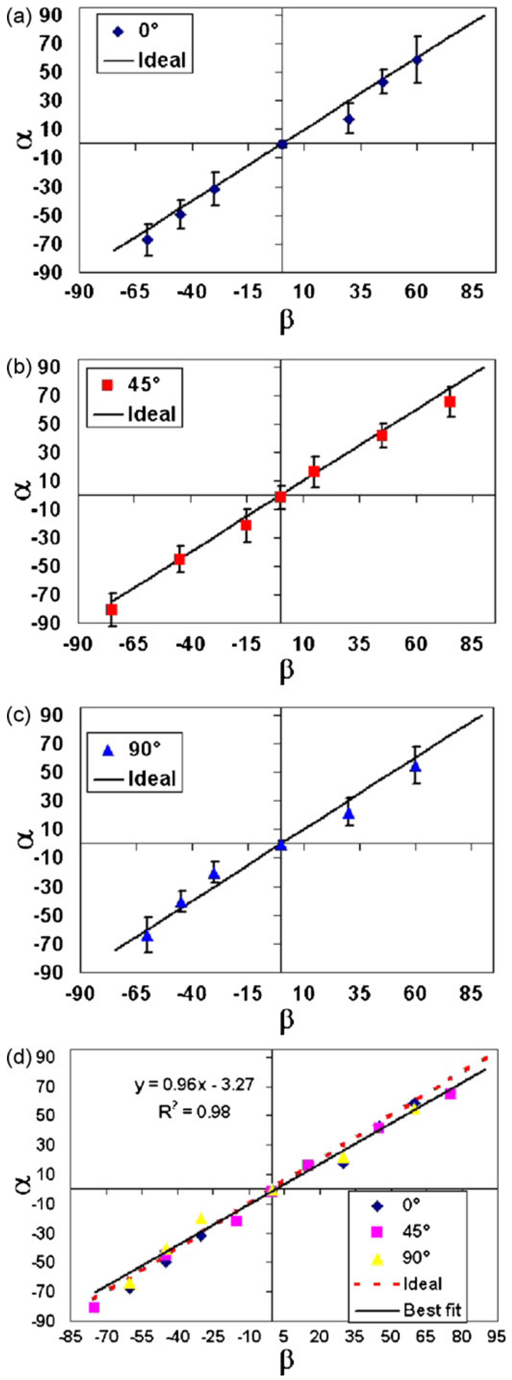

Fig. 2. Experimental results. (a–c) Plots reporting the angle a between the perceived and actual directions of motion (on the vertical axis) vs. the angle b between the actual direction of motion and the axis of the pattern on the pad for the three motion directions (0°, 45° and 90°). (d) Plot showing data from all trials and the linear fit to experimental data.

the presentation of stationary stimuli inducing illusory motion or implying motion, or to apparent motion stimuli, and even during the analysis of object shape [10,17–19,27,28].

Relatively as well to the similarities between touch and vision in the functional processing of complex dynamic stimuli, a *supramodal* representation of object and face forms has been recently shown in the ventral extrastriate pathway of sighted [1,14,21] and congenitally blind individuals [21]. In fact, visual and tactile object recognition evokes common category-specific patterns of neural activations in the ventral extrastriate cortical pathways of sighted subjects. Remarkably, also congenitally blind individuals show category-specific activations in the same cortical areas of the ventral pathway in response to tactile object recognition [21], thus suggesting that visual cortical activation during tactile discrimination tasks cannot be merely attributed to visual imagery. Recent findings also demonstrated that the occipito-parietal extrastriate areas are involved both in visual and tactile spatial discrimination tasks, thus supporting a *supramodal* organization of the dorsal stream [20,23,24]. Altogether, the ventral visual cortical pathway can therefore process information independently from the sensory modality that carries that information to the brain. Previous experiments have partially assessed hMT+ recruitment during nonspecific tactile motion perception in sighted subjects [4,11], or auditory motion in both sighted and early blind individuals [22]. Additionally, we recently verified that in both sighted and congenitally blind subjects the first areas of the dorsal processing stream also show a *supramodal* organization, and thus that tactile flow also relies on hMT+ for tactile motion discrimination [25].

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