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Processing 3D form and 3D motion: Respective contributions of attention-based and stimulus-driven activity

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ABSTRACT

This study aims at segregating the neural substrate for the 3D-form and 3D-motion attributes in structure-from-motion perception, and at disentangling the stimulus-driven and endogenous-attention-driven processing of these attributes.
Attention and stimulus were manipulated independently: participants had to detect the transitions of one attribute –form, 3D motion or colour– while the visual stimulus underwent successive transitions of all attributes. We compared the BOLD activity related to form and 3D motion in three conditions: stimulus-driven processing (unattended transitions), endogenous attentional selection (task) or both stimulus-driven processing and attentional selection (attended transitions).
In all conditions, the form versus 3D-motion contrasts revealed a clear dorsal/ventral segregation. However, while the form-related activity is consistent with previously described shape-selective areas, the activity related to 3D motion does not encompass the usual "visual motion" areas, but rather corresponds to a high-level motion system, including IPL and STS areas.
Second, we found a dissociation between the neural processing of unattended attributes and that involved in endogenous attentional selection. Areas selective for 3D-motion and form showed either increased activity at transitions of these respective attributes or decreased activity when subjects' attention was directed to a competing attribute. We propose that both facilitatory and suppressive mechanisms of attribute selection are involved depending on the conditions driving this selection. Therefore, attentional selection is not limited to an increased activity in areas processing stimulus properties, and may unveil different functional localization from stimulus modulation.

Introduction

Visual motion is a rich source of information about the environment: from motion cues only, we are able to perceive our self-motion (direction of heading), other's actions (biological motion) and, of primary interest in this study, the 3D structure and 3D motion of the surrounding objects.

Structure-from-motion (SFM) perception has been largely demonstrated and tested using dynamic random dot stimuli, for which the motion parallax (i.e. the relative motion between dots) is the only depth cue (Rogers and Graham, 1979; Braunstein and Andersen, 1984; Cornilleau-Pérès and Droulez, 1994). The neural substrate of SFM perception has been explored in various imaging studies (Orban et al., 1999; Paradis et al., 2000; see also the review by Greenlee, 2000; Kriegeskorte et al., 2003; Murray et al., 2003; Peuskens et al., 2004). Overall, optical flows generating SFM perception activate a large set of visual areas, not specific to the extraction of the structure information from motion: this SFM network includes the visual motion areas (including V2, V5+ and regions of the intraparietal sulcus); ventral areas involved in shape perception (lateral occipital and fusiform cortices; collateral sulcus) and areas presumably involved in the control of attention (in the intraparietal and precentral sulci). Our goal is to better understand the respective role of these visual and attentional areas in the processing of two different "end-products" of SFM perception: the 3D form and its 3D motion.

3D structure and 3D motion from 2D motion

The perception of 3D motion is a correlate of SFM perception. This is well illustrated by the simultaneous alternation of motion direction together with 3D shape in the bistable perception of a rotating

Abbreviations: 3D, three-dimensional; SFM, structure from motion; BOLD, blood oxygenation level dependent; (f)MRI, (functional) magnetic resonance imaging; ROI, region of interest.

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Necker's cube. This was also demonstrated mathematically by Longuet-Higgins and Prazdny (1980), who established that the 3D movements and 3D structure are recovered altogether through the same process. Extracting the 3D movements of a visual stimulus from the retinal 2D motion indeed requires non trivial processing: translations on the retina, for instance, may correspond to the rotation of a 3D stimulus around a fronto-parallel axis. Yet, little interest has been devoted to the perception of "3D motion from 2D motion" compared to the perception of structure from motion. The first aim of the present study is to disentangle the respective contributions of 3D form and 3D motion perception to the cerebral activity induced by an optical flow.

One input, two visual pathways

Although intimately associated in the optical flow, the form and 3D motion of the underlying objects are well segregated at the perceptive and physiological levels. Structure and motion direction are easily identified as two distinctive attributes of a perceived object. Form conveys information about the identity of the object while movements usually do not, even if motion has also been explored as an intrinsic property of objects (see Newell et al., 2004 and the concept of spatio-temporal signature by Stone, 1998). Importantly, 3D-form and 3D-motion attributes can vary in an independent way.

From a physiological viewpoint, form and motion are processed along two distinct visual pathways. Form processing is carried out by the ventral pathway devoted to object identification, whereas motion processing develops along the dorsal pathway devoted to visuo-spatial interactions (Ungerleider and Mishkin, 1982; Goodale, 1998). Accordingly, SFM perception should activate both the ventral and dorsal pathways.

Previous studies exploring the neural bases of SFM perception showed that both pathways were indeed activated differentially when comparing a 3D-SFM stimulus to a non-coherent 2D-motion display (Orban et al., 1999; Paradis et al., 2000; Kriegeskorte et al., 2003; Murray et al., 2003). These results indicate that visual processing within the ventral path is not limited to static cues, and that the dorsal path does not exclusively process motion information. However, these studies did not fully elucidate the respective roles of the ventral and dorsal pathways in SFM perception. Are the ventral and dorsal activities related to early-processing stages (e.g. retinal-speed analysis, extraction of depth information…); are they related to the processing of various perceptual attributes (form and 3D motion of the visual object); or do they reveal tasks implicitly performed on the object (e.g. identification, simulated manipulation, orientation judgment, etc.)?

Respective contributions of stimulus-driven and attention-related processes?

To better control the possible influence of an implicit task and disentangle the respective contribution of form and motion attributes on SFM-related activity, several authors introduced a task to focus subjects' attention on different attributes of the 3D object.[1] Activity was found predominantly in the dorsal pathway when observers attended to the direction of motion and predominantly in the ventral pathway when observers attended to the form or texture (Paradis et al., 2001; Peuskens et al., 2004). While informative, those studies tested the effect of feature-directed attention only, averaging BOLD activity over different visual conditions. Yet, different mechanisms may take place depending on whether the stimulus itself remains identical or changes over time.

In the present work, we clarify the contribution of attention-related and stimulus-driven inputs to the processing of 3D motion and structure in SFM perception. To disentangle the stimulus-driven processing from attentional selection, we independently manipulated the physical attributes of the stimulus and the participants' attention. The stimulus underwent changes of form, direction of 3D motion and colour distribution. Meanwhile, observers' attention was focused by a detection task: a visual instruction prompted them to report the transitions of either form, 3D motion or colour distribution until the next instruction.

To characterize stimulus-driven activity, we tested the effect of the form and 3D-motion transitions while participants were attending to the colour changes. In the following, these transitions are called "unattended transitions". To characterize attention-related activity, we tested, at the colour transitions, the influence of attending to form or to 3D motion. Last, to evaluate the contribution of selective attention to the visual processing of form and 3D motion, we analysed the activity elicited by the form transitions when subjects were attending to form, or by the 3D-motion transitions when subjects attended to 3D motion. These are called "attended transitions" in the following.

Methods

Participants

Eleven healthy volunteers (5 men and 6 women) aged 21–28 years took part in the study, approved by an Institutional Ethic Committee (CCPPRB). Volunteers gave their written informed consent and received a small financial compensation for their participation.

All participants had normal vision; all but one were right handed; one had a left ocular dominance. One subject was excluded from the analysis because of excessive head movements (above 3 mm displacement in translation).

Visual stimuli: SFM with transitions of form, 3D motion, and colour distribution

The visual stimuli, presented over a black background, comprised a central fixation cross and a distribution of 200 coloured dots (red and green antialiased dots, 6 pixels width, 0.27° visual angle; perceptual equiluminance between red and green was achieved for each participant using an equalisation procedure based on heterochromatic flicker photometry). During the stimulation, the dots continuously moved as if they belonged to a 3D surface oscillating in depth around a fronto-parallel axis tangent to the surface (sinusoidal oscillation: 10° maximal amplitude, 2 s period; see Paradis et al., 2000). This stimulus was viewed through a 16° diameter virtual window; moving dots could appear or disappear behind the invisible edges of this mask, but the edges of the surface were never visible.

Every 2 s, when the oscillating surface passed through the central (and initial) position, either the form, the orientation of its oscillation axis or the distribution of dot colours could change: the 3D form alternated between a paraboloid and a horse-saddle; the oscillation axis could tilt in the screen plane by an angle of 45°, 60° or 90°; part of the dot distribution (85 to 95%) could reverse colour from red to green or vice versa. The order of the transitions (form, 3D-motion direction and colour change) was randomized.

The 3D parameters of the stimulus –its surface curvature and oscillation amplitude– were chosen so that all motion and form transitions yielded a similar amount of visual acceleration. Because of the surface movement, this visual acceleration was always minimal at the centre of the screen. In order to minimize the visual change at the centre of the screen for the colour transitions as well, no dot under 1° eccentricity changed colour. Also, the percentage of dots changing

[1] Following Corbetta and other's results, the working hypothesis is that selective attention to a visual attribute enhances the activity in areas processing this attribute (Corbetta et al., 1991; Huk and Heeger, 2000). Hence, comparing conditions where subjects attended to the 3D form versus conditions where their attention was focused on the direction of motion was expected to highlight the areas specialized in 3D-form processing with respect to those specialized in 3D-motion processing.