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Exploiting the gain-modulation mechanism in parieto-motor neurons: Application to visuomotor transformations and embodied simulation

Sylvain Mahé, Raphaël Braud, Philippe Gaussier, Mathias Quoy, Alexandre Pitti *

Laboratoire ETIS - UMR CNRS 8051, Université de Cergy-Pontoise, Bat. St-Martin, 2, avenue Adolphe-Chauvin, F 95302 Cergy-Pontoise Cedex, France

HIGHLIGHTS

- We exploit the gain-field effect in parietal neurons for sensorimotor transformations.
- Construction of a body map is based on visuo-motor integration in a robotic arm.
- Error between real and estimated signals models the hidden spatial transformation.
- This feature of gain-fields neurons is used to solve the correspondence problem.
- Gain-field neurons learn external-point reference frames for tool-use and body change.

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ABSTRACT

The so-called self–other correspondence problem in imitation demands to find the transformation that maps the motor dynamics of one partner to our own. This requires a general purpose sensorimotor mechanism that transforms an external fixation-point (partner's shoulder) reference frame to one's own body-centered reference frame. We propose that the mechanism of gain-modulation observed in parietal neurons may generally serve these types of transformations by binding the sensory signals across the modalities with radial basis functions (tensor products) on the one hand and by permitting the learning of contextual reference frames on the other hand. In a shoulder–elbow robotic experiment, gain-field neurons (GF) intertwine the visuo-motor variables so that their amplitude depends on them all. In situations of modification of the body-centered reference frame, the error detected in the visuo-motor mapping can serve then to learn the transformation between the robot's current sensorimotor space and the new one. These situations occur for instance when we turn the head on its axis (visual transformation), when we use a tool (body modification), or when we interact with a partner (embodied simulation). Our results defend the idea that the biologically-inspired mechanism of gain modulation found in parietal neurons can serve as a basic structure for achieving nonlinear mapping in spatial tasks as well as in cooperative and social functions.

1. Introduction

Over the last two decades, the studies of the post-parietal cortex (PPC) have permitted to understand better the neural mechanisms involved in the spatial representation of oneself body. What we have discovered is that our body representation is far more labile as we previously thought and that the brain fully exploits the perceptual ambiguity yielded by the senses to represent spatially not only our body limbs but also the nearby objects and by extension the persons around us. The so-called mirror neurons found by Rizzolatti and his colleagues exemplify the most this discovery as they respond to action and to observation (Rizzolatti, Fadiga, Fogassi, & Gallese, 1996; Rizzolatti, Fogassi, & Gallese, 2001). Mirror neurons appear to bear out the fundamental structure for achieving perceptual, cognitive and motor functions as well as cooperative and social functions (Fogassi et al., 2005; Keysers, 2004) although its mechanism is still poorly understood.

In this perspective, the studies by Iriki in the macaque monkeys are particularly interesting as they showed evidences of a dynamical readaptation of the body schema with respect to the ongoing situation (Iriki, Tanaka, & Iwamura, 1996). By simply manipulating

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* Corresponding author. Tel.: +33 81761992602.
E-mail address: alexandre.pitti@u-cergy.fr (A. Pitti).

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the visual feedback on a TV set that a monkey scrutinizes to guide its arm motion, Iriki showed how the parietal neurons were readjusting continuously the body image (here the hand) in accordance to the new reference frame (Okanoya, Tokimoto, Kumazawa, Hihara, & Iriki, 2008). The spatial transformations performed could be as complex and nonlinear as the combination of translation, rescaling and rotation. This result was also tested on tool-use where the spatial receptive fields of the parietal neurons associated to the hand extended to entail the tool (Goldenberg & Iriki, 2007; Maravita & Iriki, 2004). In terms of social cognition, this transformation mechanism is considered to take a central place in the process of understanding others as a mean to transform someone else visuo-motor perception into our own thus simulating their actions (Fogassi et al., 2005; Lewkowicz, Delevoye-Turrell, Bailly, Andry, & Gaussier, 2013; Meltzoff, 2007; Rizzolatti et al., 2001), see Fig. 1.

Thus, one may recognize that the neural mechanisms involved in spatial representations constitute a hard problem that requires at the same time non-linear transformations as well as rapid processing. On the one hand, the PPC is ideally placed for multimodal integration since it is one of the first cortical structure to receive the sensory signals coming from the different modalities (Andersen, 1997; Pouget & Snyder, 1997). On the other hand, its role to bind fastly the sensory signals is not trivial at all since each sensory signal is encoded differently and anchored to different body part or spatial reference frame; e.g., eye-, head-, shoulder- or hand-centered. One consequence is that patients with lesions of the parietal cortex present difficulty in spatial adjustment, coordination disorders and even spatial neglect (Keysers, 2004). Moreover, the spatial disorders also pervade in the social domain particularly in autism spectrum disorders with the importance of embodied self-rotation for visual and spatial perspective-taking (Pearson, Ropar, & Hamilton, 2013; Surtees, Apperly, & Samson, 2013). These studies have revealed a lack of multimodal integration and the disability to put in perspective the spatial location of objects and persons relative to our body.

Considering the mechanisms it may involve, the discovery of reach cells and postural cells for particular orientation of the hand associated to the current context or motor plan have permitted to discriminate further the functional organization at the network level (Blohm & Crawford, 2009; Bremner & Andersen, 2012; McGuire & Sabes, 2009). Andersen and colleagues (Andersen, Essick, & Siegel, 1985; Andersen & Mountcastle, 1983) first discovered neurons firing for a specific eye saccade motor command, *modulated* by the position of the eye relative to the head. That is, this result demonstrates that (1) these neurons are bimodal neurons as they encode two information at once and that (2) their amplitude level is an informative quantity that can be modeled. Furthermore, the gain-modulation effect observed for this behavior does not correspond to a summing integration as it would be for integrate-and-fire neurons. Instead, a more correct mathematical model of the parietal neurons' response would be a multiplicative integration between the incoming sensory signals, which can be approximated as a nonlinear basis function (Pouget & Snyder, 1997).

The striking advantage of a gain-field representation of the signal is that a basis function representation may approximate any desired mapping, as it is the case for the Fourier series or the wavelet decomposition. Therefore, this kind of representation meets the requirements for a local-to-allocentric transformation because multiple reference frames can be derived from the same population of neurons allowing to use intrinsic as well as extrinsic reference frames (Bremner & Andersen, 2012; McGuire & Sabes, 2009). For instance, Shadmehr and Wise proposed that the gain-field neurons compute a fixation-centered frame by subtracting the vector between the gaze location and the hand position to derive the hand toward the target in eye-centered frame (Bremner & Andersen, 2012; Shadmehr & Wise, 2005). Following this, different robotic experiments have been conceived using the linear combination of basis functions for sensorimotor transformations (Chinellato, Antonelli, Grzyb, & del Pobil, 2011; Halgand, Soueres, Trotter, Celebrini, & Jouffrais, 2010; Hoffmann et al., 2010).

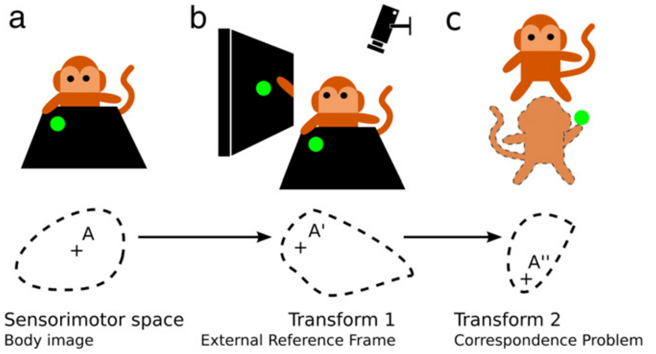

Fig. 1. The problem of the frame of reference and of sensorimotor transformation. (a) Grasping is a complicated task as it requires to learn the visuomotor space in an ego-egocentric reference frame. (b) When we observed our own action in a TV set, we change reference frame, which requires to transform the spatial information of the visual coordinates with respect into the hand coordinates. (c) The same situation occurs when we observe someone else's actions and try to imitate them; this transformation is called the correspondence problem. The point A in visual space corresponds to the point A' in the new reference frame after transformation and to the point A'' after a different transformation.

In previous works, we demonstrated how the mechanism of gain-field modulation can be applied for integrating audio–visual signals and proprioceptive feedback in a head–neck–eyes robotic device as it is for some parietal neurons (Pitti, Blanchard, Cardinaux, & Gaussier, 2012). In our studies, the gain-field neurons were successfully used to remap the location of one sound signal (in head-centered reference frame) into retina coordinates (in eye-centered reference frame). The gain-field based model enabled the system to increase the accuracy of a visual stimulus (i.e., the position of the mouth when a person speaks) by using the supplementary sound signal to estimate more precisely the spatial location of the mouth–voice stimulus.

In this paper, we consider to employ again the gain modulation mechanism but this time toward a fixation-point reference frame, external to the body (Shadmehr & Wise, 2005). We propose that the same neural architecture may permit to derive cognitive functions involved in fixation-point reference frame (such as tool-use) as well as social functions involved in perspective-taking tasks such as joint attention and imitation. To this end, we first perform a rapid learning of the visuomotor associations in a gain-field architecture with a shoulder–elbow-like robotic arm and a camera. Once its body schema is learned, a second gain-field module is added for situations of visuomotor mismatch and novelty. This second module is used to encode the new sensorimotor *task set* (Pitti, Braud, Mahé, Quoy, & Gaussier, 2013a; Pitti, Mori, Kouzuma, & Kuniyoshi, 2009) corresponding to the visuomotor distortions induced by novel fixation-centered tasks such as in front of a mirror, during tool-use or during the control of an avatar in a video game (self-observation in a TV set). In the social domain, the idea is then to retrieve the hidden visuomotor transformation responsible for the mismatch between the robot arm's own motion and what it currently sees (e.g., a person moving his/her hand aside). The hidden visuomotor transformation permits to reduce the resulting spatial error in the visual field and in the motor domain, which is associated to the so-called correspondence problem (Brass & Heyes, 2005; Heyes, 2001) and to motor imaginary (Kosslyn, Ganis, & Thompson, 2001).