Internal coordinate representations for motor adaptation and interference reduction

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Many studies have investigated the neural representation of learned dynamics by examining generalization after learning[1-4]. However, these studies have generally used dynamics that are ambiguous to the subjects — that is they could be represented in multiple coordinate systems — and then probed the representation by examining the pattern of generalization. Instead of probing generalization, we examine whether novel dynamics that are explicitly and unambiguously represented in different coordinate systems can be learned. Subjects performed reaching movements while grasping the handle of a robotic manipulandum[5] while hand position and hand orientation were measured. Center out reaching movements were performed to 6 targets in which we controlled the hand orientation at the beginning and end of each movement. After null field movements, a velocity-dependent force field was introduced. Three experimental groups performed each of the 6 movements with three different hand orientations (i.e. wrist flexed, neutral and extended). For the Cartesian group (n=6) the force field was constant in Cartesian space, that is independent of the hand orientation (Fig 1A, left). For the Object group (n=6), the force field rotated with the hand orientation (Fig 1A, middle). These two conditions mimic natural situations in which either the forces exerted by an external object do not depend on the hand orientation (e.g. pushing against a door) or depend on the hand orientation (e.g. a hand held tool). For the Anti-object group (n=6), the force field rotated in the opposite direction to the orientation of the hand (Fig 1A, right). This in theory has no more complexity than the Object-based group but does not correspond to a natural situation. A control group (n=6) performed the same number of movements using only a single hand orientation with a fixed force field.

There were no differences in the final amount of adaptation (Fig 1B) between the Cartesian (green), Object (orange) and control (black curve) groups (small decrease in learning rate for Object group). However, the Anti-object group (purple) learned significantly slower with a larger final error than the other three groups (Fig 1B,C). Together these results demonstrate that the sensorimotor control system is adaptive to the properties of the dynamics; learning just as well when they are presented unambiguously as either a function of Cartesian or hand orientation or as an ambiguous field (control group, black). However, subjects cannot learn any arbitrary coordinate system. That is when the dynamics rotate in an opposite direction to hand orientation, there is a significant reduction in the ability to learn. This demonstrates that while the sensorimotor control system is able to represent the dynamics in many coordinate systems, it cannot learn any arbitrary mapping.

In the second study, we examined the contributions of limb posture to the reduction of interference. While opposing force fields presented with matching limb posture produces strong interference, a small physical shift in the location reduces this interference significantly[6-8]. However, in these studies the separation of the endpoint location changes not only the Cartesian endpoint but also the joint configuration (shoulder and elbow) and hand orientation. Here we examine each of these components individually to examine how they reduce interference. Subjects (n=12) performed straight reaching movements with 5 configurations (Fig 2A), in which we could dissociate Cartesian, joint and object-based coordinates. This allowed us in three conditions to apply CW and CCW force fields that could be uniquely separated only based on one of the coordinate systems (Fig 2A blue and red correspond to opposite fields). Subjects adapted to all three conditions in a blocked design where the order was counterbalanced across the subjects. The largest reduction in error (and increase in force on channel trials) was found when the field direction depended on the hand orientation (Fig 2B orange). While small reductions in error were observed in the other two conditions (Fig 2B green, blue), the force compensation was low (<20%) demonstrating a significance amount of interference (Fig 2C). This demonstrates that changes in hand orientation can be used to learn separate internal representations of the external dynamics.

Together these two studies show that hand orientation-dependent fields can be learned as fast as fields fixed in space and that hand orientation has a privileged status in terms of allowing subject to learning opposing fields.

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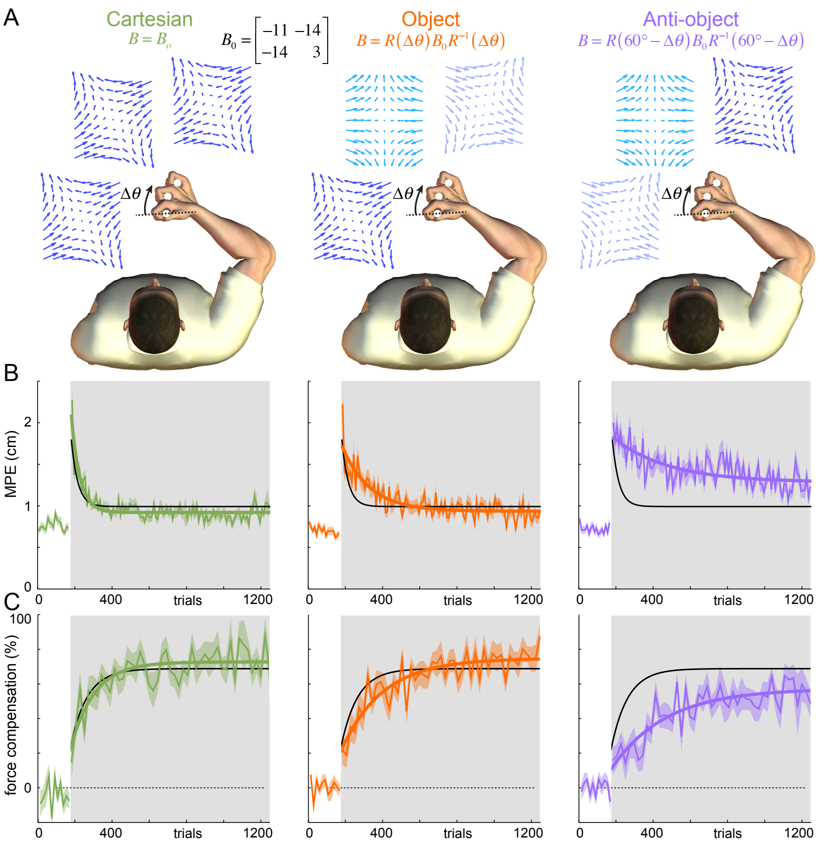

Figure 1. Adaptation to unambiguous dynamics. **A,** *left:* The Cartesian group adapted to a force field which was fixed in Cartesian space regardless of the orientation of the hand. The three fields show the force vectors as a function of velocity (zero at center) for the three different hand orientations. *middle:* The object group adapted to a force field which rotated in the same direction as the hand orientation ($\Delta\theta$). *right:* The anti-object group adapted to a force field which rotated in the opposite direction to the hand orientation. Note that the fields presented are the same as for the object group but presented at different hand orientations. All three groups performed movements in six equally spaced directions at each of the three hand orientations (30° apart). For comparison a control group performed movements in the force field B_0 with the middle hand orientation (not shown). **B,** The maximum perpendicular error (MPE) as a function of trial number for the Cartesian (green), object (orange), and anti-object (purple) groups. For comparison, on all plots the best-fit model to the control group data is shown in black. **C,** The percent force compensation (% of perfect compensation to the force field) as measured against the channel wall in channel trials for each of the groups.

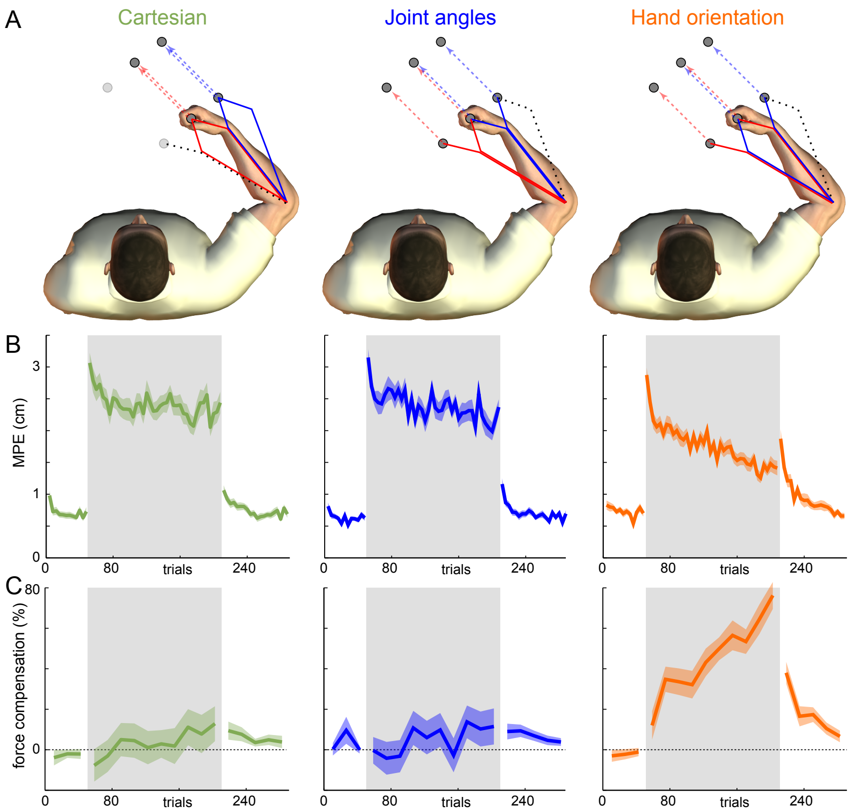

Figure 2. Contributions to reduction of interference. **A,** Subjects made short reaching movements with their upper arm in one of five limb postures. These postures were chosen such that the postures matched at least one other posture in terms of joint angle (elbow and shoulder), Cartesian endpoint, and/or hand orientation. Opposing curl force fields (denoted by red and blue colors) were then applied such that the dynamics could be uniquely separated based on only one of the three coordinate systems. In each condition four movements were performed. All subjects performed all three conditions in a random order. *left:* The Cartesian condition. Only the endpoint position uniquely separates the force fields (e.g., the two middle postures have the same elbow and shoulder angle but opposite force fields). *middle:* The joint angle condition. The two force fields are uniquely separated based on the shoulder and elbow joint angles. *right:* The hand orientation condition, where the two opposite force fields are uniquely separable only by the differences in the hand orientation. **B,** The MPE as a function of trial number for the Cartesian (green), joint angle (blue) and hand orientation (orange) conditions. **C,** The percent force compensation as measured against the channel wall in channel trials for each of the conditions.

References

1. Shadmehr, R. & Mussa-Ivaldi, F. A. *J. Neurosci.* **14,** 3208–3224 (1994).
2. Malfait, N., Shiller, D. M. & Ostry, D. J. *J. Neurosci.* **22,** 9656–9660 (2002).
3. Malfait, N., Gribble, P. L. & Ostry, D. J. *J Neurophysiol* **93,** 3327–3338 (2005).
4. Shadmehr, R. & Moussavi, Z. M. *J. Neurosci.* **20,** 7807–7815 (2000).
5. Howard, I. S., Ingram, J. N. & Wolpert, D. M. *J. Neurosci. Methods* **181,** 199–211 (2009).
6. Hwang, E. J., Donchin, O., Smith, M. A. & Shadmehr, R. *Plos Biol* **1,** E25 (2003).
7. Hwang, E. J., Smith, M. A. & Shadmehr, R. *Exp Brain Res* **173,** 425–437 (2006).
8. Howard, I. S., Wolpert, D. M. & Franklin, D. W. *J Neurophysiol* **109,** 2632–2644 (2013).