Motor equivalence and the uncontrolled manifold

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Abstract

We discuss the notion of motor equivalence in the context of speech production and argue, that a rigorous grounding of the notion needs to make use of the concept of the uncontrolled manifold. We provide a brief tutorial of the principle of the uncontrolled manifold and link it to speech articulatory movement using a simple toy example. We sketch the neuronal dynamics from which the uncontrolled manifold emerges and discuss implications for understanding flexible, context-dependent speech articulatory dynamics.

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1 Introduction

Speech is one of the most accomplished motor acts people master. Speech articulatory movements are not fixed programs that unfold invariably. The motor control involved in speech production is, instead, highly flexible and adaptive to context, articulatory intention, or emphasis. This is illustrated by the fact that we can easily speak while at the same time chewing food. (although that is not considered good manners). Maybe it is not too appetizing to visualize, but the coordination among the components of the articulatory apparatus to required to achieve this feat is amazing. Moreover, the speech articulatory apparatus has many degrees of freedom, all of which must be coordinated to achieve the appropriate spatial and temporal order from which meaningful streams of speech sounds emerge. Finally, speech movements are complex sequences of different gestures, whose timing and order is highly significant for the task.

The jaw is the only simple joint involved in speech production. Other articulators have rich internal kinematics and dynamics, including the lower and upper lip as well as the tonque, which may makes physical contact with the palate or comes close to that at multiple locations. These articulators by themselves thus represent multiple mechanical degrees of freedom, in a sense, even continuously many. Finally, the control of the glottis contributes to the formation of speech sounds, of course.

Speech may be viewed as a sequence of articulatory gestures, each of which have particular articulatory goals associated a sound of speech [11, 2]. A common perception is that these goal states are characterized by a smaller number of variables than required to described the complete articulatory apparatus. For instance, the bi-labial closure that occurs during production of a /ba/ in English can be characterized by the distance between the lips, a single variable. Similarly, the distance between the tip of the tonque and the palate determines the goal state of certain fricatives like /sh/. This view of articulatory goals suggests that for any individual articulatory gesture, the movement apparatus is redundant, having more mechanical degrees of freedom than strictly required.

One manifestation of such redundancy is the observation of motor equivalence, that is, the realization of articulatory goals in multiple different forms when the movement context changes. In a series of celebrated experiments, researchers used perturbations to different articulators to make motor equivalence evident [5, 1]. In the experiment of Kelso and colleagues, for instance, the jaw of participants was briefly pulled down on unpredictable trials while participants tried to say /bab/ or, on other trials, /baz/

[5]. The timing of the perturbation was controlled and occurred before the second consonsant. A fast compensatory reaction was observed in the upper lip as little as 40 msec after the perturbation. The upper lip moved down further than on unperturbed trials when that motion was required to achieve the bilabial closure for the second /b/ in /bab/, but did not move down when that motion was not required to produce /z/ in /baz/. Similar results have been described for perturbations to the lips and to other effectors [9].

Despite these clear patterns of behavior, conceptually the notion of motor equivalence is less well defined than it appears. Thinking through the issue, the reader will notice that the variable that describes the articulatory goal, here the bilabial closure or the distance of the tip of the tongue from the palate, is never going to be perfectly unchanged when we compare perturbed to unperturbed conditions. There may be a small change in these variables induced by the perturbation or by any other variation of articulatory conditions that may occur naturally . The notion of motor equivalence then says that the changes to these variables relevant to the articulatory goals are small compared to the other changes of the articulatory configuration not directly relevant to the articulatory goal. Those other changes of the articulatory configuration thus represent the ”motor equivalent” solution to the articulatory task.

This definition seems to presuppose two things: First, that there is a shared metric with which to compare the amount of variation that occurs at the level of the articulatory goal and the amount of variation that occurs at the level of the articulatory configuration. Second, that there is a way we can compare the many variables that describe the articulatory apparatus to the few variables that describe the articulatory goal.

The solution to these problems has been in the literature for a while, although primarily outside the field of speech articulatory coordination. The notion of the ”uncontrolled manifold” was first proposed for problems such as upright stance, shooting, or pointing movement [15, 12, 14, 17]. To illustrate the idea, think of a three-joint arm moving in a plane to point to a two-dimensional target (illustrated in Fig. 1, see also [16]). The articulatory state of this system can be described by three variables, the three joint angles. The articulatory goal is characterized by two variables, the two cartesian coordinates of the pointer tip. Motor equivalent solutions to the task are different joint configurations leading to the same location of the pointer tip. In reality, of course, the pointer tip position is never exactly reproduced. To provide evidence for motor equivalence, we would need to show that the pointer tip differs less across conditions than does the joint configuration. The two problems are obvious: The position of the pointer tip is measured in centimeters, the configuration of joint angles in degrees or radians. Moreover, the pointer tip has two variables, while the joint configuration has three.

The solution to both problems is based on the commitment to a shared space within which the system is embedded. We have commonly used the space of joint configurations as that embedding space, with a common metric across all joint angles (so degrees of shoulder angle are compared to degrees of wrist angle). For any given task value of the task variables (here, pointer tip position), we consider the set of joint configurations that all lead to that same value of the task variables (pointer tip pointing to the same location in two-dimensional space). This is, generally, a smooth manifold of joint configurations, illustrated in Fig. 1, but can be approximated by the linear subspace that is tangent to that manifold for purposes of statistical analysis (see [16] for discussion). We have called the manifold the ”uncontrolled manifold” based on the idea that the central nervous system controls less precisely or even not at all, which configuration within that manifold is being realized, while control perpendicular to that manifold is used to achieve the task of keeping or moving the pointer tip to its desired location. A related idea has been proposed in [6] in the context of speech motion, but at the level of muscular redundancy. These authors have proposed that variability of muscular activation patterns occurs preferentially within those patterns, that lead to the same pattern of articulatory motion.

The concept of the uncontrolled manifold has been used to provide a task-specific form of variance analysis, in which the spontaneous variability from trial to trial was used to find signatures of this structure. In many different experimental systems, evidence was found for much larger variance within the subspace that leaves the goal-state invariant than perpendicular to that subspace [15, 12, 14, 17].

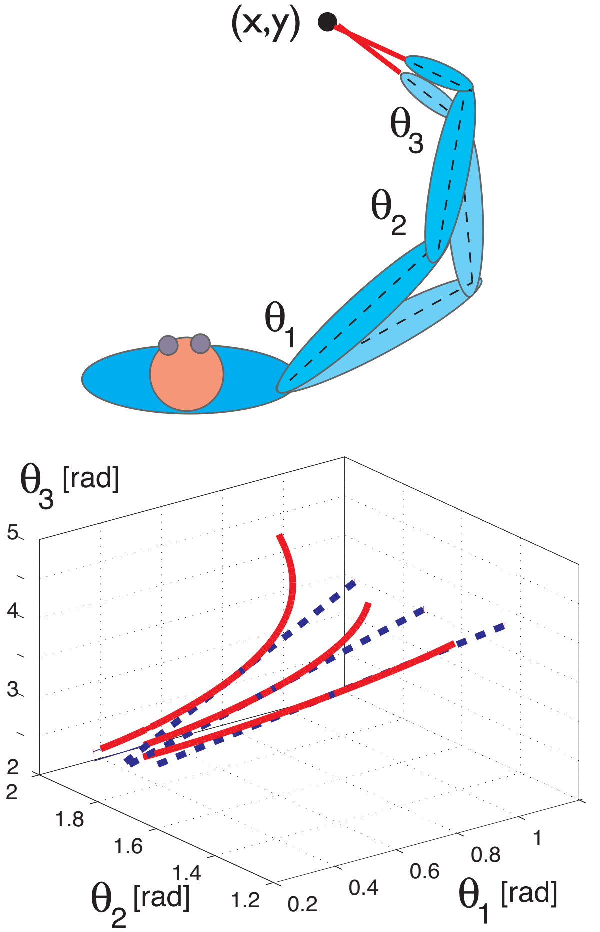

Figure 1: For a three-joint arm pointing at a two-dimensional target (top), the goal-equivalent set of arm configurations forms or each end-effector position a one-dimensional uncontrolled manifold (solid) in the three-dimensional joint space (bottom). The linearized manifolds (null-spaces) are shown as dashed lines).

Another way of employing this solution to the two problems is to look at changes in joint configuration induced by perturbations. We have done so in a recent study of upright stance, in which the support surface on which participants stood was suddenly, but briefly, accelerated [13]. In this case we were interested in comparing the joint configuration of upright stance before and after the perturbation. Relevant task variables include the horizontal position of the center of mass of the body (critical for maintaining mechanical stability: this point must remain over the footprint to prevent falling). Again, a naive conception of motor equivalence would postulate that a new joint configuration is generated in response to the perturbation that leads to the same horizontal position of the Center of Mass. The Center of Mass does not, however, remain perfectly invariant. It is moved somewhat. The intuition that this is a minor change compared to the configurational change induced by the perturbation cannot be made exact due to the same difficulty of comparing variables with different units and dimensionality. The only way to make this comparison is to use the concept of the uncontrolled manifold. Motor equivalence is confirmed if the joint configuration before and after the perturbation differ more within the uncontrolled manifold than orthogonal to it.

We therefore computed the difference vector between the two joint configurations before and after the perturbation and projected this vector onto the subspace within which the horizontal position of the Center of Mass remains unchanged and the orthogonal subspace, within which that position changes. We found that the difference vector lay primarily within the goal-equivalent subspace. This provided evidence for motor equivalence. The length of the two projections into the two subspaces must be normalized appropriately, taking into account the different dimensionalities of these two subspaces. This is because even completely uncorrelated degrees of freedom would have a tendency to produce more change in a subspace with larger number of dimensions than in a lower-dimensional subspace (see [16] for such methodological details).

We are not experts in the area of speech production, so the following sketch is merely a proposal to the community interested in speech production, illustrated within a very much simplified setting. Figure 2 is a rough sketch of the outer speech articulatory apparatus, the jaw, and the upper and lower lip. If we consider bilabial aperture the relevant task variable for articulatory goals such as /b/ or /p/, we can link the degrees of freedom to this task variable with a simple geometrical model:

$$a = +y_j - y_{ul} - y_{ll}$$

where a is the bilabial apperture, y_j is the position of the jaw, (relative to the palate) y_{ul} is the position of the upper lip (relative to the palate), and y_{ll} is the position of the lower lip (relative to the jaw). This is the simplest scenario in which only three degrees of freedom are used. Still, the system is kinematically redundant, because three degrees of freedom are available for one goal-variable. The nullspace (here identical to the uncontrolled manifold, as the equation is linear) can be determined analytically and is spanned by the vectors $(1, 1, 0)/\sqrt{2}$ and $(1, 0, 1)/\sqrt{2}$ (see Fig. 2). Analysis of motor equivalence would examine differences between articulatory configurations with and without perturbation. The difference vector would be projected onto the nullspace and its orthogonal component. The squared length of each projection would be divided by the number of dimensions of each subspace (one for the nullspace, two for the orthogonal space). These numbers can then be compared. Motor equivalence is proven if more of the difference ends up lying in the nullspace than in the orthogonal space.

How may motor equivalence arise? A recent neuronal dynamic model of the uncontrolled manifold suggests what kind of mechanisms may be at play [8]. Figure 3 gives a survey over the model. The model contains components responsible for planning goal-states and for initiating and timing the motor act, all formulated at the level of the task variables. We shall gloss over these levels here, just assuming that a task-level trajectory is generated. At the other end, the model contains the biomechnical dynamics of the effector system as well as an associated muscle-joint model that takes into account the impedance properties of muscles (based on a simplified version of [3]). The descending motor command to the muscle-joint system is, therefore, a virtual joint angle and velocity vector. The centerpiece of the model is the critical structure. A neuronal dynamics generates the time courses of these virtual joint angle vectors based on an input signal that described the time course of the task variable. In other words, this dynamics achieves the transformation from task space into joint space. It does so as a neuronal dynamics, by coupling the virtual joint velocities such that joint velocity vectors that leave the task variable unchanged are decoupled from virtual joint velocity vectors that change the task variable. This accounts for many of the signatures of the "uncontrolled manifold".

A critical component of the model is "back-coupling", that is, feedback from the real effector into the neuronal dynamics that generates the motor command at the level of virtual joint vectors. This coupling affects primarily the subspace of goal-

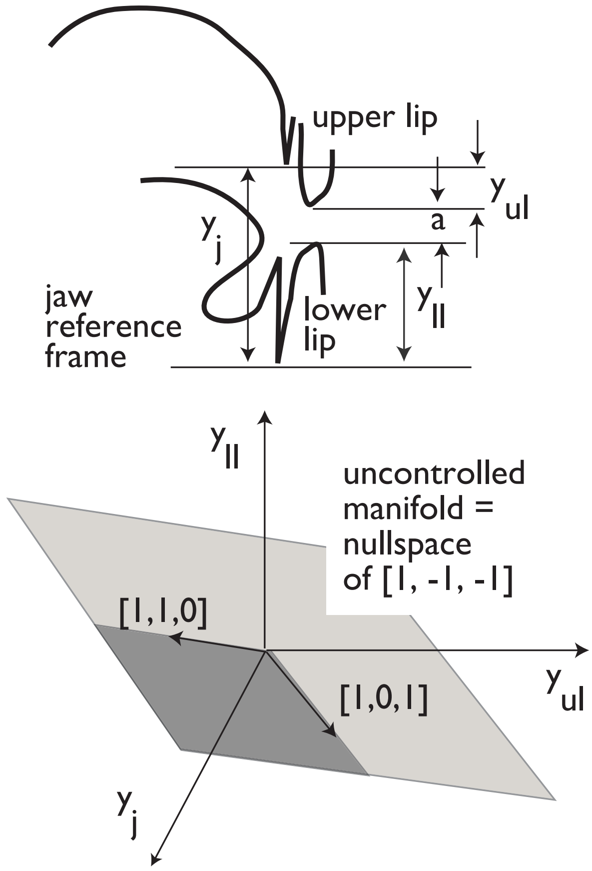

Figure 2: A caricature of the articulatory apparatus is shown with definitions for three degrees of freedom: the jaw position (relative position of palate and jaw-based reference frames) and the position of the upper and lower lip, all of which contribute to the bilabial aperture. On bottom we have sketched the uncontrolled manifold that flows from the bilabial aperture as task variable.

equivalent joint configurations and explains motor equivalence: Deviations of the real from the virtual joint trajectory lead to an update of the virtual joint trajectory within the uncontrolled manifold, generating a new, motor-equivalent plan. Without this back-coupling, a model of this general structure may account for some aspects of the uncontrolled manifold, but for motor equivalence as observed in experiments involving perturbations. Clearly, feedback from the periphery is required into order to sense the effect of mechanical perturbations. The motor command is updated and this updating generically leads to the observed signature of motor equivalence.

This is not the first model, that relates task level

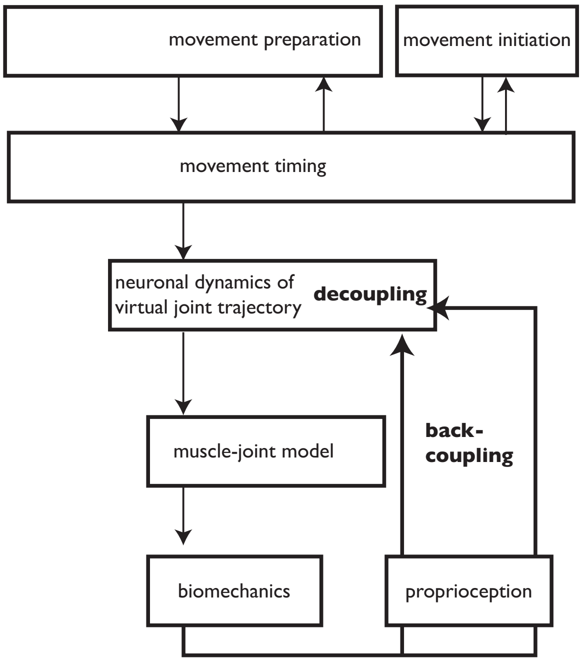

Figure 3: A schematic of the model of [8].

plans to effector-level trajectories through neuronal dynamics (see, e.g., [11]), although the concept of decoupling within that neuronal dynamics is new. Other modelling approaches to motor equivalence invoke a similar form of feedback from the periphery. as our "back-coupling". The DIVA model [4], for instance, postulates that proprioceptive and tactile feedback updates the orosensory direction vector, that acts as a motor command in this model. This loop thus feeds back into the task level of the articulatory model, not the effector level. This earlier model is much more detailed and richly mapped onto the experimental literature than our present sketch. It does not invoke the concept of an uncontrolled manifold and documents motor equivalence in qualitative terms. Current versions of this line of modeling use the concept of motor equivalence to analyze the variance of articulatory states in a way that seems to be consistent with the notion of an uncontrolled manifold, although the idea is not formalized [10]. Maybe the link between motor equivalence and the uncontrolled manifold sketched here could be useful for researchers interested in the rich coordination structure of the speech production system.

What is the functional significance of the decoupling and backcoupling principles in the neuronal dynamics of the joint configuration vector? In principle, both forms of coupling make it possible to accomodate additional constraints for an articulatory task. This idea has been used in robotic implementations, in which nullspace motion is used to safeguard secondary tasks or constraints [7]. In speech production, the sequential nature of the task makes that each articulatory goal must be achieved in a broad variety of contexts. The preceding and the upcoming gestures, the stress pattern as well as other, expressive aspects of speech production such as prosody or volume all provide constraints to which the production of any particular gesture must accomodate. Coupling degrees of freedom such that those combinations that support a current articulatory goal are decoupled from those that are free to adjust to context may be an organizational principle underlying the rich and specific structuring of the speech production system.

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