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Manual Skill Generalization Enhanced by Negative Viscosity

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Huang FC, Patton JL, Mussa-Ivaldi FA. Manual skill generalization enhanced by negative viscosity. *J Neurophysiol* 104: 2008–2019, 2010. First published July 21, 2010; doi:10.1152/jn.00433.2009. Recent human-machine interaction studies have suggested that movement augmented with negative viscosity can enhance performance and can even promote better motor learning. To test this, we investigated how negative viscosity influences motor adaptation to an environment where forces acted only in one axis of motion. Using a force-feedback device, subjects performed free exploratory movements with a purely inertia generating forces proportional to hand acceleration, negative viscosity generating destabilizing forces proportional to hand velocity, or a combination of the acceleration and velocity fields. After training, we evaluated each subject's ability to perform circular movements in only the inertial field. *Combined* training resulted in lowest error and revealed similar responses as *inertia* training in catch trials. These findings are remarkable because negative viscosity, available only during training, evidently enhanced learning when combined with inertia. This success in generalization is consistent with the ability of the nervous system to decompose the perturbing forces into velocity and acceleration dependent components. Compared with inertia, the combined group exhibited a broader range of speeds along the direction of maximal perturbing force. Broader exploration was also correlated with better performance in subsequent evaluation trials; this suggests that negative viscosity improved performance by enhancing identification of each force field. These findings shed light on a new way to enhance sensorimotor adaptation through robot-applied augmentation of mechanics.

INTRODUCTION

The influence of human-machine interactions on motor learning offers exciting new prospects for the retraining of skills after neural injury. One promising form of such interactions is to augment movement using robot-applied forces (Aguirre-Ollinger et al. 2007; Kazerooni 1996). However, learning and generalization of motor skills under these conditions is not yet well understood. For healthy individuals, researchers have already demonstrated that force fields presented during robotic training can cause dramatic adaptation in manual coordination with relatively brief exercise (Patton et al. 2006; Shadmehr and Mussa-Ivaldi 1994). For individuals with motor impairment, an environment that augments movement could reduce workload while promoting increased movement and sensorimotor re-training.

In this investigation, we are interested in the influence of robot-augmented motion on motor learning and generalization through the use of a simple *negative impedance*. In a broad definition, an impedance maps the motion imposed by an agent on the environment into a reaction force exerted by the environment on the agent (Hogan 1985). The sign of the impedance is a matter of convention. Here we follow the convention that a *negative* impedance generates a force that is in the same direction of the applied motion. While interaction with positive impedances such as weights or elastic bands provides resistance to movement and promotes strengthening, negative impedances tend to amplify movement and arise only from an active agent such as a therapist or a robotic interface. The challenge with any training paradigm, however, is whether the individual can both improve performance on the task at hand *and* generalize learning to unpracticed conditions.

Experimental evidence suggests that training in a given environment can interfere with learning and performance in another (Brashers-Krug et al. 1996; Hinder et al. 2007; Krakauer et al. 2006; Salimi et al. 2000; Tong et al. 2002). Such interference could depend on whether strategies compete for neural resources (Bays et al. 2005). However, it is not obvious what circumstances evoke such competition or could in some cases aid learning. The human motor system can evidently integrate visuo-motor and force adaptation to perform successfully in combined conditions (Davidson and Wolpert 2004; Ghahramani and Wolpert 1997). Researchers have also demonstrated that the appropriate force field training can facilitate learning of a kinematic distortion (Wei and Patton 2004). A key question is whether training in one type of environment (perhaps enhanced by technology) can benefit performance better than practicing in that target environment alone. Understanding such a process could have a significant impact on training applications including sports, piloting, and therapy.

The ability to transfer skills across ostensibly different conditions suggests the use of control schemes that make use of common modular elements. Researchers have shown evidence for feedforward models or internal representations of the environment that mediate motor planning (Kawato 1999). Such schemes have been shown for simple dynamical properties such as gravity (McIntyre et al. 2001), inertia (Gentili et al. 2004; Kreifeldt and Chuang 1979; Solomon et al. 1989), and resonant frequency (Huang et al. 2007; Mah and Mussa-Ivaldi 2003; Piccoli and Kulkarni 2005). One possibility is that the motor system is capable of separating an internal representation into its constituent elements. On the other hand, the motor system could focus learning of some elements, while suppress learning of others. If such modular learning is possible, it would mean that some forms of enhancements to training environments could differ from real world conditions and yet offer comparable or perhaps even improved learning.

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Enhanced environments might offer training advantages over even normal conditions. Researchers have shown improved learning from augmenting error feedback (Matsuoka et al. 2007; Wei et al. 2005) and by transiently applying an amplifying force field to the leg in locomotor training (Emken and Reinkensmeyer 2005; Emken et al. 2007). Negative impedances share similarities with error-augmented environments because they offer intensified sensory-motor experiences. One advantage to negative impedance as a form of error augmentation, however, is that it requires no specification of any task. Consequently, the performers can even train by freely exploring the space of movements, choosing how to direct their own learning. Such a training paradigm serves as an excellent measure of learning generalization because the structured evaluation after training (for example, performing circular movements) is certain to differ from the exploratory practice.

The critical question in employing a negative impedance in manual training is whether any potential benefits will be corrupted by inappropriate learning. Negative impedances tend to amplify motion by introducing instability. While the motor system might be capable of skill transfer between such dissimilar environments, two clear alternative outcomes of training might also occur. First, the motor system might adopt a feedforward strategy that is specific to the negative impedance and then fail to make a transition in the final evaluation, thus supporting the philosophy of "teach to the test." Another alternative outcome is that the destabilizing effects of the negative impedance could simply lead to stiffening via co-contraction (Milner and Cloutier 1993, 1998). Such increases in stiffness could even be directionally specific to cope with varying directions in stability (Burdet et al. 2001; Franklin et al. 2007). Such co-contraction can be frustrating due to excessive exertion on the part of the subject. The experimental technique of *catch trials*, where the forces are unexpectedly removed or changed, can often reveal whether there are feedforward components in the control.

We investigated how learning an inertial force field might be supplemented with negative viscosity. We examined how a period of training with both negative viscosity and inertia can benefit performance when the viscosity is removed and only the inertial field remains. We compared the effectiveness of this training to training with an inertial field alone and also compared it with training with negative viscosity alone. In addition, we examine how the exploratory actions themselves might be influenced by negative viscosity and related to better learning. Our findings indeed demonstrate that exploratory training with negative viscosity improves learning and generalization, at least in part by promoting broader exploration during training. This suggests an intriguing new approach for machine-facilitated learning, an approach in which the trained task is augmented by a destabilizing force field. This may impact training areas such as sports, piloting, tele-operation, and therapy.

METHODS

Human subjects

In this study, 26 healthy individuals were randomly assigned to either the inertia or the combined subject groups. We later included a third group with 13 healthy individuals participated as a part of the negative viscosity group. All participants reported have normal or corrected to normal vision. Each subject provided informed consent in accordance with Northwestern University Institutional Review Board. Individuals were not paid for their participation. Two subjects reported being left handed. Subjects performed the task with their dominant arm.

Apparatus and implementation of anisotropic force fields

We asked subjects to control the movement of a two-degress-of-freedom planar force-feedback device (Fig. 1) described elsewhere (Patton and Mussa-Ivaldi 2004). We programmed the device to present forces representing unfamiliar mechanical behavior: anisotropic inertia and/or negative viscosity. We chose such conditions to mimic the dynamic coordination and inherent anisotropy of the arm (Flanagan and Lolley 2001) but still pose an unfamiliar and challenging motor task for healthy subjects to learn. During the task, the handle responded as if it were a physical inertia along one axis, while no external force was present in the perpendicular axis. In some cases, we included anisotropic negative viscosity aligned with the axis of the inertia. We selected five orientations for the anisotropic force fields: θ_m = 0, 36, 72, 108, 144° with respect to the lateral plane. Endpoint forces $F_x(t)$ and $F_y(t)$ approximating inertial and viscous force fields were presented according to

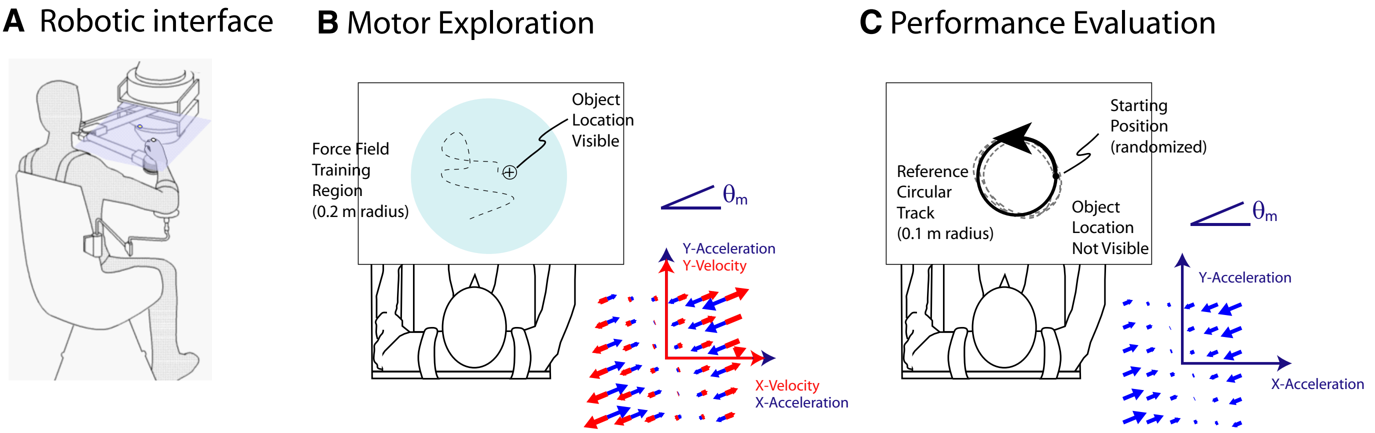

FIG. 1. *A*: we presented various anisotropic inertial force fields with a force-feedback planar manipulandum. *B*: subjects were allowed to freely interact with each field in a "free exploration" stage. Feedback of the cursor position was available for each free exploration stage. *C*: following exploration, subjects made counter-clockwise circular movements with the manipulandum during task performance evaluation trials at random starting locations of a 0.1 m radius circular track. Feedback of the cursor position was omitted during the main treatment trial blocks.

$$\begin{bmatrix} F_x(t) \\ F_y(t) \end{bmatrix} = R^t \begin{bmatrix} 0 & 0 \\ 0 & m \end{bmatrix} R \begin{bmatrix} \ddot{x}(t) \\ \ddot{y}(t) \end{bmatrix} + R^t \begin{bmatrix} 0 & 0 \\ 0 & b \end{bmatrix} R \begin{bmatrix} \dot{x}(t) \\ \dot{y}(y) \end{bmatrix}$$

where

$$R = \begin{bmatrix} \cos\theta_m & \sin\theta_m \\ -\sin\theta_m & \cos\theta_m \end{bmatrix}. \qquad (1)$$

We chose a mass parameter m of 0 or 3 kg and a viscosity parameter b of either 0 or -10 N-s/m. With the rotation matrix R, anisotropic force fields were selected representing various orientations. Note that the rotation is applied to both the inertial and viscous matrices in *Eq. 1*. A set of rotation angles thus specifies a family of force fields that are identical except for the axis on which inertial and viscous forces act. In fact, every force field can be considered as effectively the same, simply by transforming the measured data into an object-centered coordinate system (see *Data analysis*). While curl (Gandolfo et al. 1996) and saddle force fields of previous studies also included elements of negative viscosity (Shadmehr and Mussa-Ivaldi 1994), the resulting interaction featured forces that acted orthogonal to the direction of motion. In contrast, the environments of the current study produce force interactions only along the direction of motion.

Using MATLAB XPC-Target (Natick, MA), a computer performed real-time differentiation and filtering (4th order, low-pass cut-off at 11 Hz) of the robot joint-angle encoder data and calculated estimates of the velocity and acceleration of the handle endpoint. The resulting simulated inertial and viscous force fields exhibited delays of <40 ms. Data were collected at 100 Hz. The basic rate of dynamics simulation was 2 kHz. Using the environment described in the preceding text, we designed an experiment paradigm in which subjects were presented anisotropic force fields with varying orientations.

We chose to employ multiple related force field conditions to focus our investigation on the ability of the motor system to identify changes and appropriately adapt a control strategy. First we were particularly interested in the ability of the motor system to form internal representations of novel conditions. To minimize the influence of interference between force field orientations, the conditions were presented in blocks separated by contextual cues, which we will describe in the next section. The use of only one orientation may have prompted subjects to rely primarily on iterative corrections rather than an active identification process to identify the properties of new virtual object. Second, a given force field will likely exhibit a unique interaction with the anisotropy of the arm endpoint impedance. Using many orientations will provide an understanding of how manual performance is influenced by control scheme as opposed to the mechanics of the arm.

Training and evaluation experiment block

Before we provide details of the schedule of conditions in this study, we will first describe the basic experiment block, which included brief training followed by a series of performance evaluations. Using the robotic manipulandum subjects performed: training with free exploratory movements (*free exploration*) followed by several trials (12) of a prescribed circular movement (*performance evaluation*). Our experiment design tested how subjects adapted to a new force field orientation in each basic experiment block.

Using an overhead projector mounted on the ceiling, real-time feedback of the handle position, visual reference cues, and experiment instructions were presented on a horizontal surface overlaying the planar workspace of the arm (see Fig. 1). Visual reference cues included a circular reference track (shown in white, 0.1 m radius), which acted as a target path for performance evaluation, or a larger circular region (blue), indicating the bounds of movement for the free exploration portions of the experiment.

During free exploration, subjects were instructed to move the object at their discretion using various directions, speeds, and positions within a circular region (0.2 m radius centered within the workspace). Subjects were told that the exploration stage would feature an environment similar to that experienced during the subsequent performance evaluation stage but could have missing or added elements. No further instruction was provided about strategy during the exploration stage. The computer signaled the user to halt free exploration after 15 m of handle endpoint total travel.

For the performance evaluation portions of the experiment, subjects were instructed to move the robotic interface in three complete counter-clockwise revolutions at about one revolution per second. Subjects were told to achieve accurate and smooth performance as much as possible in circular movements about a target track. After each trial, feedback was also provided as to whether average movement speed was too fast or slow. No further instruction was provided about strategy for the evaluation. Random starting locations were indicated on the circular track at $\pi/8$ intervals.

Schedule of experiment conditions

Using the experiment block described in the preceding text, we presented subjects with a sequence of treatments (or series of blocks). In the *baseline treatment,* presented first, forces were primarily absent. To familiarize subjects with the task goals, visual feedback of the handle endpoint was available in the performance evaluation stages in the first three blocks. The last two blocks of the baseline treatment consisted of a free exploration stage, 10 task performance trials and 2 *initial exposure* catch trials. Also in the last two blocks, visual feedback of the handle endpoint was removed during evaluation trials. Initial exposure catch trials introduced an unexpected force field (either $\theta_m = 72$ or 144°). Data from the initial exposure and baseline trials served as a reference for how the later training influenced performance with and without an active force field. Note that we only presented a subset of force field orientations in initial exposure trials to limit learning during baseline. A brief break (~3 min) was provided before the next treatment was presented.

After the baseline treatment, the *main treatment* was presented, consisting of five blocks, each in turn associated with a different anisotropic force field. Each block began with a free exploration stage, followed by 10 performance evaluation trials. The five conditions represented the varying orientations of anisotropic inertia ($\theta_m = 0$, 36, 72, 108, 144°). During the main treatment, visual feedback was presented only during free exploration. During normal evaluation trials, the performance evaluation included only the inertial field. In addition to the performance evaluations, two catch trials were randomly presented following free exploration, in which the field was covertly turned off. Catch trials were used as means to analyze the degree to which subjects employed feedforward control in anticipation of the training environment. Catch trials were used to assess to the degree to which subjects adopted a feedforward control scheme.

The experiment groups differed in terms of presence of viscous and inertial field elements during free exploration. However, each group was presented with only the inertial field during the evaluation portions of the experiment. During exploration, the negative viscosity group was presented with no external inertial forces and a viscosity term was set to -10 N*s/m. The inertia group was presented with no external viscosity while the inertial term was set to 3 kg. The combined group was presented with both negative viscosity and inertia during exploration. Note that though negative viscosity tends to decrease stability, the physical viscosity of the arm and robot likely offset the low levels of negative viscosity presented. Note also, that it is possible that some dissipation is produced through volitional control, further adding to overall stability.

Data analysis

Our results section will be organized to first present a summary of performance evaluation comparisons for each subject group. For the performance evaluations, we wished to quantify how well subjects learned to compensate for anisotropic inertia. We judged that more learning would be evidenced by the recovery of circular motion during normal trials and less circularity during catch trials. Next we will characterize movement patterns during the exploration stage that may have contributed to learning differences. We examine how training conditions differed in terms of how the observed distribution of speeds and how such differences related to subsequent performance.

We devised as our main metric of performance, the *radial deviation*, to assess the degree of movement circularity. With a given position measurement in the plane (x_i, y_i), we calculated the radial deviation according to $e_i = r_i - \bar{r}_i$, where the $r_i = \sqrt{x_i^2 + y_i^2}$ is the instantaneous distance to the center, and $\bar{r}_i$ is the mean distance for a given trial. Note that this metric considers the mean radius of movement rather than the template circular track as the reference for ideal movement (Please see RESULTS for a discussion of absolute error). Because visual feedback was omitted during evaluation, we considered the ability of subjects to recover circular motion to be the most appropriate measure of successful adaptation to the anisotropic force field compared. We present averaged trajectories of the radial deviation over time for each group (see Fig. 3). These averaged trajectories depict the occurrence of cyclic trends error in terms of magnitude and phase. Besides average trends in error, we analyzed performance in terms of the maximum radial deviation observed during each trial. We chose the maximum value, as opposed to the average, to more accurately assess the success of feedforward control as opposed to any on-line adaptation or error correction. As a final metric, these results are presented in terms of the normalized radial deviation (observed performance posttraining divided by average baseline performance). A result of 100% observed during the evaluation or catch trials (see Fig. 3) would indicate fully recovered performance with respect to baseline while a greater percentage indicates error greater than baseline persists. This analysis served as a measure for how well subjects recovered baseline performance after free exploration and how sensitive performance was to unexpected removal of the force field.

For the statistical analysis of performance, our aims were first to detect whether improvements occurred for each group and then characterize group differences in improvement. According to our hypothesis, the quality of learning during free exploration would differ by group and be revealed in performance evaluation trials. Using the metric described in the preceding text, we performed paired *t*-test (2-tail) to assess whether performance changed between initial exposure and evaluation following training. We compared performance between subjects groups, using an ANOVA with two-way interactions among three experiment factors: subject group (combined, inertia, negative viscosity), force field orientation (1–5), and the sequence of evaluation trials (1–10). Having found significant group differences, we then wished to compare the relative success of learning between groups. To correct for multiple pair-wise comparisons, we then performed Tukey's post hoc honest significant difference (HSD) tests on performance in the evaluation and catch trials (all 5 orientations). The threshold level of significance for both ANOVA and post hoc tests was set at $\alpha = 0.05$.

In addition to analyzing radial deviation during task performance trials, we examined movement during the free exploration stage in terms of movement along the primary and secondary axes of each force field. Due to the anisotropy of each force field, one axis of movement exhibits significant forces (primary), while the orthogonal axis exhibits no forces (secondary). While the radial deviation analysis described in the preceding text provided a practical measure of performance in a global reference frame, it is useful to employ such an object-centered coordinate system to help separate the influences of the external forces versus effects from the anisotropy of the arm. To do so, we computed components of speed as projected on the primary and secondary axes. Note that with this transformation of movement, the force fields at each orientation can be considered together. Furthermore, any anisotropic effects of the arm are lessened because they are distributed across multiple field orientations.

To visualize differences in exploration behavior between groups, we tabulated the observed speed states for each instance of free exploration and presented the results as contour plots of the mean distributions (see Fig. 4, *top*) for each group. Rather than calculating distributions along individual ordinates, we were interested in representing how the speed of the handle varied throughout planar motion. As such, we plotted the distribution of speeds along the axes of motion (along and orthogonal to the axis of loading) for combinations of states. We divided the data into 100 bins between 0 and 1.5 m/s, which resulted in a 100 × 100 grid of possible speed combinations over two dimensions. For each grid point, we computed the number of observations for each subject during an episode of training, calculated as a percentage of the total observations. The resulting plots are averaged across all subjects for a group. Each color indicates regions of constant density, while intervening white spaces indicate transition between the intervals of density. The closer the color bands are, the steeper the transition between regions.

Beyond comparing differences in performance, we wished to assess to what degree individuals learned the specific structure of the presented force field environments. We devised the *speed specificity ratio*, defined as ratio of the 95th percentiles of speed along the primary axis over that of the scalar speed. This metric describes the total extent of speeds exhibited along the axis of loading during exploration. Other metrics such as the average or SD of speed could also reflect the range of exploration but requires an assumption of normally distributed movement data. Similar to the concept of bandwidth in frequency analysis, we wish to characterize the extent of system excitation, which may be nonuniformly distributed in the possible space of speeds. Furthermore, because exploration patterns will differ across subjects and even between different episodes of exploration within subject, we chose the range of scalar speed as the normalization factor. This metric then conveys how the extent of activity is exhibited along an axis of interest, normalized by the extent of all observed activity. This metrics ranges from zero (no activity) to unity (all activity) of movement expressed along the axis of loading, and approaches $\sqrt{2/2}$ for isotropic activity.

We expected that speed specificity ratio described in the preceding text would reflect differences in the efficacy of learning for each group. Following ANOVA of speed specificity results, we performed Tukey's HSD comparisons, first averaging across all force field orientations, to determine if there were group differences in exploration behavior. To determine how exploration behavior influenced learning, we then performed regression analyses on the speed specificity ratio, with a data point for each instance of exploration (or a single exploration stage with a given field orientation), versus the mean radial deviation of the 10 subsequent performance trials. We obtained regression slope, R^2, and P values for each group as measures of how sensitive performance was to variations in prior exploration behavior. We organized our regression results first for all instances of exploration taken together and then second by individual subject. These regression analyses provide a crucial probe into whether the adaptation exhibited by a subject demonstrates specificity in learning. In contrast, it is possible that subjects exhibit nonspecific adaptation, for example, a general co-contraction of muscles that enables robustness against a variety of external disturbances. Consequently, the regression analyses complement the use of catch-trials to detect not only the presence of feedforward control schemes, but the presence of such learned strategies that correspond appropriately to the given evaluation environments.

RESULTS

Subjects from each group typically exhibited adaptation to changes in inertial force fields although systematic errors persisted indicating incomplete learning. During free exploration (see Fig. 2*A*), handle movement revealed a variety of manipulation behaviors. Note the changes between circular patterns and free-form movements at different periods of free exploration. This variation shows that subjects did not rely on repeated practice alone as preparation. Typical trajectories (see Fig. 2*B*) characteristic of each trial type reveal circular movements during baseline (null-field) trials, systematic cyclic errors during initial exposure trials, a return to more circular movement in evaluation trials, and finally increased error in catch (null-field) trials. Catch trials exhibited a sharp change in the orientation of ellipse patterns compared with the initial exposure to the force field, consistent with a feedforward control scheme specific to each force field orientation. These results show that subjects successfully learned from free exploratory movements because subjects were able to adopt specialized control schemes appropriate for the changes in inertial anisotropy.

Summary of performance evaluations

Before analyzing differences between groups, we first established whether each group learned feedforward control specific to the target environment of anisotropic inertia. To do so, we followed the reasoning established in research of sensorimotor adaptation to visual distortions (Held and Rekosh 1963) and to novel force field (Shadmehr and Mussa-Ivaldi 1994) environments: *1*) determine if performance improves between an initial brief exposure versus performance following training in novel conditions and *2*) determine if performance if error increases on "catch-trials" or covert removal of the novel environment with respect to baseline conditions.

We observed changes in performance before and after the main treatment sequence indicating that subjects from each group exhibited some adaptation to the inertial field (see Fig. 3). Radial error deviation typically reduced between initial exposure and evaluation trials following free exploration for each group (paired *t*-test, 2-tailed: combined, 27.7%, P = 4.8e-4, t = 4.74, df = 12, SD = 2.0%; inertia, 17.6%, P = 0.3e-2, t = 2.61, df = 12, SD = 2.5%; negative viscosity, 21.3%, P = 9.7e-2, t = 1.80, df = 12, SD = 4.3%), though changes were only significant for the combined and inertia groups. Between null-field baseline and catch trials following free exploration, radial error deviation typically increased for each group (paired *t*-test, 2-tailed: combined, 63.3%, P = 1.1e-5, t = 7.16, df = 12, SD = 1.6; inertia, 72.8%, P = 9.0e-8, t = 11.34, df = 12, SD = 1.2; negative viscosity, 77.41%, P = 6.1e-4, t = 4.60, df = 12, SD = 3.1). Meeting the two criteria described in the preceding text, these results showed that the combined and inertia groups exhibited learning of feedforward control appropriate to the inertia field. In contrast, while the negative viscosity group evidently formed some kind of feedforward plan as evidenced by significant error increases in null-field trials, their lack of improvement in evaluation indicates learning was not appropriate for the inertia conditions. Note that these results do not imply that subject employed exclusively feedforward control nor that the use of stiffness was insignificant. Instead these findings show that subjects did not employ stiffness as the primary mode of compensation for the presented force fields.

For evaluation trials, repeated measures ANOVA for the maximum radial deviation metric revealed significant main effects from the exploration type (between-groups) factor [F(2,36) = 5.93, MSE = 29.29, P = 5.9e-3] as well as the within-group factors: force field orientation [F(4,144) = 3.30, MSE = 4.26, P = 1.3e-2] and trial sequence [F(9, 324) = 22.87, MSE = 4.95, P < 2.2e-16]. These results signify that while there were differences due to the type of training, performance changes also occurred over the course of repeated evaluation trials. In addition, it is clear that not all orientations presented the same level of difficulty. We observed significant two-way interactions between exploration type and orientation [F(8,144) = 2.34, MSE = 3.03, P = 2.1e-2] between exploration type and trial sequence [F(18,324) = 8.75, MSE = 1.89, P < 2.2e-16] and between trial sequence and orientation [F(36,1296) = 2.51, MSE = 0.56, P = 2.5e-6]. These inter-

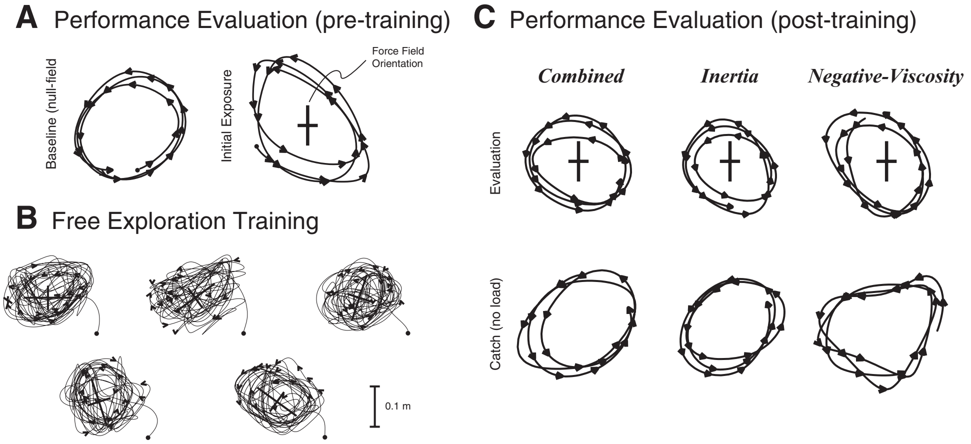

FIG. 2. Typical handle trajectories during evaluations for 1 training condition reveal differences between trial types. →, time progression. *A*: curvature is most consistent in the baseline (null-field) condition. Systematic distortions arise during initial exposure with unexpected anisotropic inertial field. *B*: for each new orientation, a free exploration stage was presented prior to performance evaluation. Handle trajectories for each orientation (indicated by longer —) reveal wide variability. *C*: performance evaluation errors were typically less than initial exposure. Catch (null-field) trials exhibit systematic errors of similar magnitude with respect to initial exposure but with sharply different orientation. Such changes in performance between *A* and *C* are characteristic of learning feedforward control specific to training. Typical trajectory shapes by inertia and combined groups was fairly similar, though some differences in circularity and consistency are apparent. The negative viscosity group, however, demonstrates large deviations from circularity and larger variability in both trial types, which suggests a strategy incompatible with force or null field conditions.

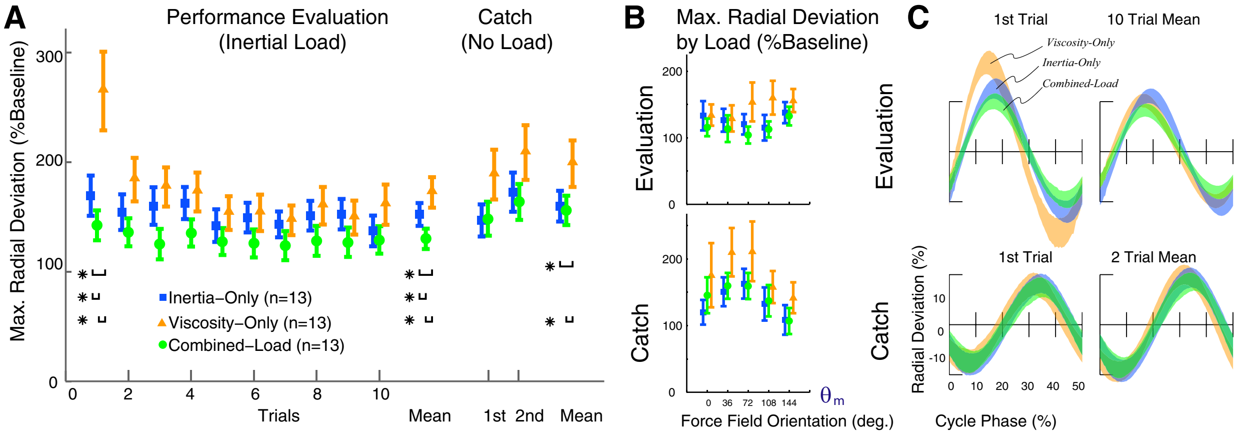

FIG. 3. *A*: combined (inertia and negative viscosity) training resulted in lower radial error deviation (*top left*) compared with the inertia and negative viscosity (22.2 and 42.4%). Error bars represent 95% CI across all subjects. Larger initial error with negative viscosity in evaluation (123.6 and 95.7%) and catch trials (42.7 and 38.9%) relative to combined and inertia, suggests learning incompatible with inertial or null-field conditions. Catch trials (*right*) indicates similar feedforward strategies between inertia and combined groups. *B*: combined training resulted in less sensitivity of error to changes in force field orientation in evaluation trials (θ_m) compared with the other groups, which suggests more successful identification of environment properties. *C*: average error trajectories along the primary axis of anisotropy (*right,* CI across all orientations and subjects) for the 1st, 2nd trials, and overall mean, exhibit sharp phase differences between evaluation (upper) and catch (lower) trials—a trend characteristic of adopting feedforward control specific to training conditions. In evaluation trials, the combined group exhibited lowest error amplitudes and similar phase to inertia. In contrast, negative viscosity exhibited relative phase lead and largest errors, which suggests a somewhat different learned strategy.

actions suggest that the type of training influenced the degree to which subjects exhibited continued performance changes in evaluation trials as well as how sensitive subjects were to changes in force field orientation.

Pair-wise comparisons revealed significant differences between groups. Post hoc Tukey HSD tests revealed that the combined group exhibited less overall error than inertia (22.2%; CI: 13.6, 30.9; P = 5.9e-09) and negative viscosity (42.4%; CI: 24.0, 51.1; P = 3.3e-11). Overall radial deviation for negative viscosity was also higher than inertia (20.2%; CI: 11.6, 28.9; P = 1.4e-07). As a measure of the immediate training effect, comparisons of first evaluation trial only results revealed that negative viscosity exhibited larger radial deviation than combined (123.6%; CI: 80.9, 164.4 P = 1.11e-11) and inertia (95.7%; CI: 54.0, 137.5 P = 1.12e-11). First trial performance differences between combined and inertia groups were not significant (26.9%; CI: −14.8, 68.6 P = 0.83). While these results focus on radial deviation relative to the mean observed radius, a similar analysis was performed on absolute radial error. The maximum absolute errors were in fact comparable among the combined, inertia, and negative viscosity training groups (0.044 ± 0.014, 0.044 ± 0.012, 0.046 ± 0.016 m) , which shows that the differences between groups were primarily in terms of learning feedforward planning as opposed to changes in visual-proprioceptive remapping.

While we focus our analysis on the average performance across all force field conditions, we noted a significant influence from force field orientation (see Fig. 3*B*). These trends can be attributed to the interaction between the force field and the arm biomechanics. In addition, it is clear from this analysis that the combined load exhibited less sensitivity to the variation in force field orientation relative to the other groups; this is also consistent with the idea of improved identification of the presented inertial fields. Combined training resulted in less sensitivity to changes in force field orientation compared with the other groups, Pair-wise comparisons by force field orientation revealed that combined training resulted in significantly lower error than inertia training for 0° (28.5%; CI: 0.5, 46.5; P = 4.1e-2) and 72° (31.3%; CI: 3.3, 59.2 P = 1.3e-2). combined and negative viscosity group differences were significant for 72 (75.5%; CI: 47.5, 103.5; P = 3.3e-11) and 108° (67.3%; CI: 39.4, 95.3 P = 1.3e-2). Combined training resulted in significantly lower error than negative viscosity training for 72 (44.2%; CI: 16.3, 72.2; P = 3.3e-11) and 108° (48.6%; CI: 20.7, 76.6 P = 4.3e-7). For the group comparisons in the preceding text, similar results were found the other force field orientations although the results did not achieve significance.

In these results, the dependency of performance on both group and orientation suggests that adaptation responses differed according to expected stability. For inertia and combined groups, larger radial deviation occurred for orientations closer to lateral directions versus fore-aft. For example, for combined, the 144° orientation exhibited larger radial deviation with respect to 72 (mean 45.7, CI: 17.3, 73.7, P = 3.41e-6) and 108° (mean 34.3, CI: 6.4, 62.3, P = 2.91e-3). In contrast, for negative viscosity, smaller radial deviations occurred in the lateral directions. For negative viscosity, the 36° orientation exhibited smaller radial deviation with respect to 72 (mean −38.7, CI: −66.7, −0.11, P = 2.75e-4) and 108° (mean −41.9, CI: −70.0, −13.9, P = 4.13e-5). Milner (2004) found that feedforward learning and co-contraction varied depending on the stability in each movement direction.

Analysis of catch trials reveals strong aftereffects from each group although only the negative viscosity training resulted in group differences. For catch trials, repeated measures ANOVA for the maximum radial deviation metric revealed significant main effects from the between-groups factor of exploration type [F(2,36) = 4.47, MSE = 7.26, P = 1.84e-2] as well as the within-group factors of orientation [F(4,144) = 20.92, MSE = 9.86, P = 1.31e-13] and trial sequence [F(1,36) = 14.72, MSE = 4.08, P = 4.83e-4] . Interactions were not significant. In contrast to evaluation trial results, comparisons between groups with post hoc Tukey HSD tests revealed that differences in catch trials between combined and inertia groups were not significant (3.7%; CI:-16.8, 24.3; $P = 0.90$). Overall maximum radial deviation for negative viscosity was higher than inertia (42.7%; CI: 22.1, 63.2; $P = 4.58\text{e-}06$) and combined (38.9%; CI: 18.4, 59.5; $P = 3.26\text{e-}05$).

Because speed and accuracy coupling are typically observed in human performance, we analyzed the influence of experiment factors on linear speed during performance evaluations. In contrast to radial deviation results, repeated measures ANOVA for linear speed revealed no significant main effects from exploration type [$F(2,36) = 0.582$, MSE = 0.3092, $P = 0.564$]. However, we did observe that the orientation of anisotropic inertia did influence speed [F(4,144) = 16.48, MSE = 0.3971, $P = 3.84\text{e-}11$]. The interaction between exploration type and orientation was also significant [$F(8,144) = 3.5443$, MSE = 0.0854, $P = 8.93\text{e-}4$]. Post hoc Tukey HSD tests, however, did not reveal significant differences in speed between groups. Hence these findings suggest that while speed variations were observed, the dominant influence of experimental factors was on accuracy.

While quantifying maximum radial error deviation provided an overall measure of performance success, radial deviation trajectories over time (see Fig. 3) can reveal some indications of feedforward control. During catch trials, the absence of a feedforward scheme should have resulted in negligible radial deviations because no external forces disturb movement. Furthermore, we observed significant radial deviation magnitudes and characteristic phase shifts between catch trials relative to initial exposure trials. This suggests that for each group some form of feedforward control schemes were in use. This near reversal in phase is analogous to how aftereffects following adaptation mirror the direct-effects of reaching movements subject to force field training (Shadmehr and Mussa-Ivaldi 1994). Thus the observed phase change suggests that subject did not rely strongly on a stiffness-based strategy. Systematic differences between groups suggest differences in the type of learning. While overlap can be seen between the data for each group, evaluation trials revealed lowest error amplitudes for the combined group. Catch (null-field) trials reveal similar error magnitudes for each group. In both evaluation and catch trials, similar phase occurs for the combined and inertia groups, while a noticeable phase lead relative to the other groups is exhibited by the negative viscosity group. It is also important to note that the trajectories given in Fig. 3 only demonstrates the average recurring error trends and can fail to capture the occurrence of initial or irregular deviations. As such, in the analysis of catch conditions, the maximum radial deviation provides a better metric of how groups differ in the use of feedforward control.

The analysis of evaluation and catch trials in the preceding text demonstrate difference between groups that were notable even despite possible further adaptation following training. The influence of trial sequence on both evaluation and catch trials suggest some adaptation within the period of performance evaluation. Note, however, that because all groups are presented with a similar exposure to evaluation and catch trials, these tests serves as fair comparison of the relative merits of each training condition in terms of how it translates to skill during performance evaluation. Note that while significant error in catch conditions indeed suggests strategies with feedforward control, subjects in this experiment could plausibly exhibit feedforward control that includes inertial and/or negative viscosity. For the negative viscosity group, radial deviation results were higher for *both* evaluation and catch conditions, which suggests that training with negative viscosity alone led to a feedforward scheme that was incompatible with both the inertial and null-field conditions. For the combined training group, any existing stiffness diminishes rapidly (as evidenced by catch trials), and apparently without sacrifice to performance during evaluations.

While the focus of our analysis is how well subjects recover circular motion, an important consideration is whether training affected the subsequent size of circular movements during evaluations. One possibility is that increases in co-contraction induced from training might cause reduction in movement extent. In fact, we observed the opposite trend for the combined and negative viscosity training groups. We observed differences between groups in mean radius (mean: 115.3 ± 15.4, 109.4 ± 14.9, 114.5 ± 16.5 (SD) mm, respectively for combined, inertia, negative viscosity, respectively). The inertia group both exhibited significantly smaller average radius than that of the combined (5.87 mm; CI: 3.84, 7.90; $P = 8.2\text{e-}11$) and negative viscosity (5.12 mm; CI: 3.09,5.12; $P = 1.1\text{e-}8$) groups according to Tukey HSD post hoc tests. Differences between combined and negative viscosity groups were not significant (7.48 mm; CI: 1.28, 2.77; $P = 0.66$). These results suggest that the inclusion of negative viscosity prompted increases in movement extent.

To determine if the increasing the size of circular movements provides a performance advantage, we performed regression analyses for each group between average radial deviation (% of trial mean radius) and radius (mm). We observed only low negative correlations ($R^2 = 0.013$, $b = -0.244$, $F = 8.82$, $P = 3.10\text{e-}4$; $R^2 = 0.050$, $b = -0.652$, $F = 34.37$, $P = 2.22\text{e-}16$; $R^2 = 0.049$, $b = -0.552$, $F = 33.25$, $P = 1.25\text{-e}8$, respectively, for combined, inertia, negative viscosity). These results show that radial deviation tends to decrease with increasing mean radius. Because the combined group actually exhibited slightly larger mean radius relative to inertia training, the observed changes in preferred movement extent apparently did not confer a performance advantage. It was the plausible the absence of negative viscosity in evaluation trials would cause a decrease in movement extent because subjects of the combined training condition were no longer supplied with movement amplification. Instead the pattern of increased movement magnitude suggests adoption of greater feedforward control.

Analysis of exploration behavior

In terms of general observations of free exploration training, we found that the mean inertial forces observed for the inertia and combined groups were, respectively, 5.52 ± 2.02 and 6.15 ± 1.82 N. The mean viscous forces observed during free exploration for the negative viscosity and combined groups were, respectively, 2.05 ± 0.35 and 1.66 ± 0.37 N. The mean completion times were 36.4 ± 8.2, 32.2 ± 4.5, and 35.5 ± 7.5 s, respectively, for inertia, negative viscosity, and combined groups.

Having identified group differences in the performance evaluation, we wish to determine how force field conditions in the exploration stage could have led to the observed differences in learning. No differences were observed for position states, indicating similar spatial extents of exploration between groups. Differences in range of scalar speeds (measured as 95th percentiles) were significant between the negative viscosity group compared with inertia (mean difference: 0.18 m/s; CI: 0.02, 0.34; $P = 2.73\text{e-}2$) and compared with combined (mean difference: 0.21 m/s; CI: 0.05, 0.38; $P = 6.96\text{e-}3$) but were comparable between the combined and inertia groups (mean difference: −0.04 m/s; CI: −0.20, 0.13; $P = 8.51\text{e-}1$). Similar trends were found for scalar acceleration. We did, however, observe key differences between the subject groups in terms of movement along the primary axis of the force field, which suggests that including negative viscosity promoted a wider range of dynamics particular to each force field orientation. Trends for the range of speeds and accelerations were similar, and group differences for each of these variables were significant.

As representative results, we provide speed analyses in the following section. Contour plots of the speed distributions during free exploration (Fig. 4*A, top*) in terms of the primary and secondary axes and averaged over all subjects and force field orientations revealed differences in movement behavior for each group. Each contour plot exhibited a peak value at lower speeds with apparent diminishing concentration of observations at higher speeds. The negative viscosity and inertia groups, however, exhibit biases toward the primary and secondary axes, respectively, likely due to the lower impedance in one axis of movement.

We next examined whether there was a difference in the *directions* that subjects moved during free exploration phase by looking at the speed specificity ratios. This measure showed the greatest activity along the primary axis from the combined group (Fig. 4*A, right*). ANOVA of the speed specificity ratio results revealed significant effects from the subject group factor ($P < 2.0\text{e-}16$), while the influence of orientation did not achieve significance ($P = 6.45\text{e-}2$). According Tukey's HSD tests, we found that the average speed specificity was larger for the combined group compared with the inertia group (0.074, CI: 0.035, 0.112, $P = 1.05\text{e-}4$). The negative viscosity group exhibited larger average speed specificity compared with the combined (0.095, CI: 0.057, 0.133, $P = 1.62\text{e-}6$) and inertia groups (0.169, CI: 0.130,0.207, $P = 2.10\text{e-}12$). These trends indicate that free exploration tends toward the direction of lower impedance and that negative viscosity shifts activity onto the degrees of freedom for which it is active.

Correlation of exploration behavior and performance

Having established how differences in training influenced movement during exploration, we now examine whether such differences can predict subsequent success in the performance evaluation phase. As shown in Fig. 4*B*, linear regressions between the speed specificity ratio for all instances of exploration (all force field orientations and subjects) and subsequent performance (average of 10 trials) revealed low but significant correlations only for combined ($P = 3.39\text{e-}2$) and inertia groups ($P = 2.22\text{e-}4$); this indicates that more exploration along the primary axis of the force field enabled better performance in the final evaluation phase. In contrast, the negative viscosity training group showed greater specificity along the secondary axis compared with the combined (0.095, I:0.057, 0.133, $P = 1.62\text{e-}6$) and inertia groups (0.169, CI: 0.130,0.207, $P = 2.10\text{e-}12$). The lack of inertial forces during training evidently resulted in poorer preparation for the performance evaluation trials.

Similar results associating exploration directions and final performance were also found from a subject-by subject analysis. We computed individual regression analyses for each subject in which we examined the correlation between the speed specificity ratios for each force field orientation and the associated performance evaluation results (mean of 10 trials). *t*-test confirmed that slopes (means ± SD) on a per subject basis for both combined (-0.11 ± 0.17, $R^2 = 0.35 \pm 0.34$, $P = 3.50\text{e-}2$) and inertia (-0.14 ± 0.17, $R^2 = 0.38 \pm 0.34$, $P = 3.46\text{e-}2$) groups were significantly less than zero, indicat-

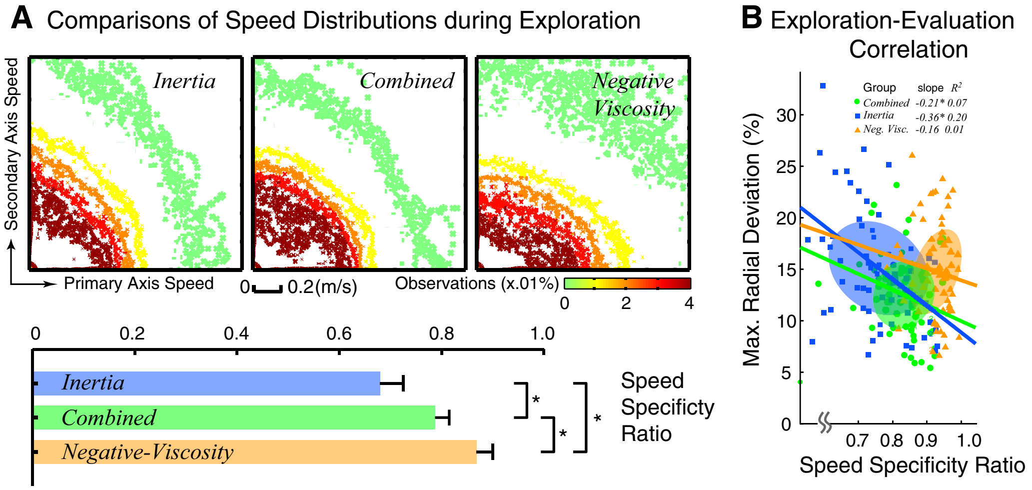

FIG. 4. *A*: contour plots (*top*) of speed distributions (average of all subjects and field orientations) over the force field axes, revealed differences in preferred movements during free exploration. Combined and negative viscosity training exhibited a clear shift of activity to the primary axis (larger robot applied force). The speed specificity ratio *(below*), or the proportion of speed observations along the primary axis, was greater (0.074, CI:0.035, 0.112, $P = 1.05\text{e-}4$) with combined relative to inertia training. *B*: linear regressions between the speed specificity and subsequent performance evaluations (average of 10 trials) revealed low but significant correlations for combined ($P = 3.39\text{e-}2$) and inertia groups ($P = 2.22\text{e-}4$), which indicated that more exploration along the primary axis enabled better task preparation when inertia was present. While negative viscosity training resulted in greater specificity relative to combined (0.095, CI:0.057, 0.133, $P = 1.62\text{e-}6$) and *Inertia* (0.169, CI:0.130,0.207, $P = 2.10\text{e-}12$), the lack of inertial forces during training evidently resulted in poorer preparation.

ing that lower radial deviations were associated greater speed specificity. The slope for negative viscosity group (-0.050 ± 0.21, $R^2 = 0.25 \pm 0.22$, $P = 4.2e\text{-}1$) was not significantly different from zero, which suggests that speed specificity did not influence performance when the inertial field was absent during exploration.

DISCUSSION

Our findings demonstrate that training with negative viscosity can improve learning of an object manipulation task, achieving even better performance than training with the nominal conditions. Subjects of the combined group exhibited performance evaluations with the lowest error magnitudes while achieving comparable catch trial magnitudes as inertia training. Our analysis suggests that training with combined inertia and negative viscosity alters the efficiency of internal model formation by promoting broader exploration (see Fig. 4). We argue then that the motor system is able to generalize learning from the combined to the pure inertial environment by preserving the shared features between environments.

Success in task switching

Switching between the combined and isolated inertial conditions could have plausibly resulted in a learning aftereffect that degrades performance, yet our results demonstrate that skill transfer can occur successfully between such environments. The motor system has been shown to be capable of specialized adaptation to a viscous environment, for example, containing negative and positive impedance directions (Shadmehr and Mussa-Ivaldi 1994). However, in the current study, adaptation to a negative viscosity would have increased error amplitude for both evaluation and catch trials because negative viscosity was absent in these conditions. Indeed results from the negative viscosity group suggest a strategy inappropriate for evaluation conditions (see Fig. 3). The rapid decrease in error following the first trial post exploration can be attributed to either a re-adaptation to the inertial field during evaluation trials or an increase in co-contraction. Training with the combined force field have could have plausibly caused subjects to adopt of a feedforward policy containing both inertia and negative viscosity elements. Yet in contrast to the negative viscosity group, exploration with combined-field did not incur large error in the first trial post exploration, which suggests no conflict between the learned strategy and the environment.

The success in switching between environments observed in this study is consistent with *decomposition,* or a process of separating an internal representation into separable elements. One possibility is that the motor system learns each element of a composite field and is able to suppress expression of a particular element as needed, for example control specific to negative viscosity. Successful decomposition could be affected by how respective strategies compete for or share neural resources. For example, investigators have observed only partial success in switching between position and velocity-based force fields (Bays et al. 2005). On the other hand, Krakauer and colleagues (1999) report that the strategies for visual distortions and force fields did not interfere; this perhaps shows an example of noncompeting strategies. The distinct task stages of exploration and prescribed movement patterns presented in this study may provided cues to facilitate the necessary changes in strategy (Imamizu et al. 2007; Krouchev and Kalaska 2003). While it remains to be seen which environments are amenable to successful decomposition, the results provided here suggest at least one condition in which final performance can benefit from a training environment that features a composition of mechanical behaviors. More study is needed, however, to understand how switching between movements patterns influences skill transfer between environments with overlapping mechanical properties.

While decomposition is a likely candidate, success in task switching might also be explained by a bias toward adapting to more familiar mechanical behavior. Although negative viscosity dramatically increased speed and acceleration profiles during exploration for the combined training group, the motor system might simply be more accustomed to tuning representations of inertia as opposed to negative viscosity. Such a bias might also be due to the relatively brief exposure to training. Consequently, the performance changes exhibited by each group were likely observed at a point of incomplete adaptation. It is evident from the significant error in evaluation trials (see Fig. 2) that the performance has not returned to baseline, indicating that further improvement was possible. However, the negative viscosity group exhibited the largest error during catch trials, which suggests that rather significant feedforward learning of the velocity-based force field can in fact occur. Further study is needed to determine how different component gains, or dosages of training, might change the efficiency of learning the individual elements of a combined field.

Evidence of improved internal model formation

Beyond demonstrating improved performance, our results also allow inferences on the form of improved learning accomplished by the combined group. In response to perturbing forces from the environment, the motor system could adopt either a feedforward control scheme or a more general strategy of increased stiffness (Milner 2002, 2004), or it could use some combination of these (Takahashi et al. 2001). Some of these possibilities can be ruled out. It seems unlikely that subjects of any group relied only on a stiffness strategy because catch conditions revealed significant error magnitudes with characteristic changes in trajectory shape (see Fig. 2). Furthermore, if the combined group only increased stiffening via co-contraction, the error would have been smaller in both evaluation and catch trials, which was not observed in our data. And as we have already argued in the preceding text, feedforward control that predicts negative viscosity alone could only increase error and hence could not explain any improvement in performance.

Instead the performance advantage exhibited by the combined group is consistent with a combination of improved learning of the inertial force fields and simultaneously increasing in stiffness. Because negative damping is destabilizing, it is reasonable that the combined group would maintain some increased stiffening when training was over. Yet comparison of catch trial results suggests at least similar feedforward strategies between the combined and inertia groups. However, it is difficult to evaluate the relative amount of feedforward learning solely on the basis of the size of the aftereffects because performance necessarily reflects a mixture of stiffness and feedforward control. We posit that the combined group must have learned improved feedforward control that predicts the inertial force fields, while simultaneously increasing in stiffness. Such a combined strategy would reduce error in evaluation conditions but would contribute competing effects on catch error magnitudes.

Learning through broader exploration

Beyond success in task switching, further explanation is needed for how the combined training actually resulted in superior performance compared with controls. Our analysis of free exploration revealed that training with negative viscosity increased the range of experienced speeds along the primary axis of the force field. Beyond the impact of modifying behavior during exploration, our correlation analysis showed that both inertia and combined groups demonstrated a relationship between training and learning. Broader exploration along the primary axis of the force field (greater speed specificity ratio) was associated with better task performance. Thus these results provide evidence that the combined training group acquired more specialized control schemes corresponding to *each* presented force field. This specificity contradicts the scenario that performance gains from combined training were due to co-contraction because such a strategy is typically considered to involve nonspecific stiffening.

This investigation demonstrated that motor system exhibits some ability to generalize between free and prescribed movements and can improve such learning with more thorough exploration. The current literature suggests that encouraging variability is only as effective as repeated practice for a ballistic task (Shoenfelt et al. 2002). On the other hand, other researchers note that practice variability can be especially effective if task parameters change (Giuffrida et al. 2002) and can promote more stable performance (Shea et al. 2001). Note, however, that the current study featured variability in terms of continuous free manipulation as opposed to a schedule of prescribed movement patterns of varying direction, speed, or extent. In such a context, free exploration may facilitate the identification of environment properties, for example inertial or visco-elastic parameters (Huang et al. 2006). From a systems perspective, a broader excitation of movement states can inform a more complete representation of model parameters (Ljung 1999). Nonetheless both free exploration and variable practice provide the opportunity to direct one's own movement goals.

Other training environments might also promote greater overall movement, for example, the presence of time-dependent force perturbations. However, earlier observations (Conditt and Mussa-Ivaldi 1999; Karniel and Mussa-Ivaldi 2003) have shown that the nervous system adapts more easily to state-dependent forces. Furthermore, our findings suggest that negative viscosity promoted the learning of strategies that were not only broader in range, but more specific to the particular force-motion relationships of each force field. While this study featured changes in mechanics, it is plausible that task instructions and biofeedback could also promote greater exploration. The presentation of anisotropic negative viscosity, however, provoked specific kinematic changes that may be difficult to enforce with instructions.

Sensorimotor enhancement by augmentation

Negative viscosity effectively introduces heightened sensorimotor experience in a manner similar to *error augmentation* (Wei et al. 2005; Matsuoka et al. 2007) because it amplifies the effects of intended actions. Augmentation presumably facilitates learning by strengthening the associations between motor actions and sensory consequences, for example as found in the use of sensory channel augmentation (Sveistrup 2004; Todorov et al. 1997). In contrast to perceptual changes, however, altering mechanics necessitates changes in the energetic requirements and stability: two important factors in promoting motor adaptation. Inertial characteristics of objects and the arm evidently influence preferred movements (Schaal et al. 1996; Sabes et al. 1998). In these cases, the hand endpoint impedance clearly influences the sensitivity of movement to motor input, and subsequently the strength of motor associations.

Another important consideration is that the decrease in stability associated with negative viscosity could have promoted an increase of attention. The influence of attention could be further investigated, for example, using a task combining inertia with motivational factors that are not associated with greater exploration (for example, monetary reward or disturbing loud noises when the subject deviates from a prescribed movement). Note, however, that for the current study, only training in the combined condition could have plausibly increased attention *and* provided training specifically pertaining to inertial forces.

Limitations

While our findings suggest enhanced learning from training with negative viscosity, there are some limitations to the results that are worth considering. Greater feedforward control typically produces two effects: reduced error in evaluation conditions and increased error in catch conditions. Because we identified differences between groups only in evaluation conditions, the results appear intermediate to what would be expected for either changes in purely feedforward or purely stiffness. One might argue that the observed differences might be explained by the nonlinearities of a stiffness-based scheme alone. However, such differences would likely be more evident in catch trials, where errors are of larger magnitude so that

TABLE 1. *Experiment schedule*

	Field	Vision	Trials
Baseline Treatment			
x3 blocks			
Free exploration	—	✓	
Task performance	—	✓	12
x2 blocks			
Free exploration	—	✓	
Task performance			
Baseline	—	—	10
Initial exposure (inertia, θ_m = 72, 144°)	✓	—	2
Main Treatment			
x5 blocks, randomized by force field orientation			
Free exploration (*by group*) *inertia*, or *negative-viscosity*, or *combined*	✓	✓	
Task performance (all groups)			
Evaluation (inertia)	✓	—	10
Catch	—	—	2

differences in error correction due to impedance would be more pronounced. In contrast, our results found the largest differences between groups in the evaluation trials, where errors were smaller and feedforward control dominates.

Another limitation of this study is that we did not assess how co-contraction in particular changed with training or how it differed between groups. We note, however, that the critical issue is how the formation of feedforward control schemes occurs when training with augmentative negative viscosity. Experimental probes such as EMG analysis could plausibly detect changes in co-contraction; however such tools do not readily avail the form of feedforward learning, for example, in terms of separate effects for inertia versus negative viscosity. Furthermore because increases in feedforward control could occur simultaneously with increases in co-contraction, differences in feedforward learning would be difficult to assess on the basis of muscle activation patterns. Modeling approaches are needed to determine how the different forms of feedforward learning are likely to manifest in terms of the error trajectories during both normal and catch conditions. Further investigation is needed to determine how feedforward control can occur alongside co-contraction when training with destabilizing forces and how these two forms of control evolve after exposure. As we discuss in the next section, our correlation analysis provide an indirect assessment of feedforward learning, by examining to what degree the character of motor behavior during exploration could predict success in subsequent performance evaluations.

Implications to Rehabilitation

Enhancing motor learning by including destabilizing force field could have important implications to rehabilitation and other motor skill training endeavors. Amplifying movement is especially important for individuals with motor impairment who have limited movement capabilities (Johnson et al. 2005; Kahn et al. 2006; Krebs et al. 2003). Training in an unfamiliar environment could plausibly cause some initial co-contraction. The critical question is how the learner can in the long term extract the relevant aspects of the training conditions (in this case inertia) apart from the irrelevant scaffolding elements (negative viscosity) that are absent in the evaluation conditions. For the purpose of supporting training, it could be justified to provoke a temporary change of greater co-contraction through training with negative viscosity if such training could also promote a lasting change in the learning improved arm coordination.

The current study demonstrates the capacity of the motor system to train with a form of energetic assistance and then successfully apply learned skills to a completely passive environment. Researchers have already shown (Housman et al. 2009; Sanchez et al. 2006) that stroke survivors can improve manual skills with a device that reduces the influence of gravity on the arm. Similar to negative viscosity, such conditions facilitate intended movements yet preserve the inertial aspects of arm dynamics. Further study is needed to determine how training with a negative impedance influences long term skill acquisition as well as how such conditions compare with other forms of robotic training.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

REFERENCES

Aguirre-Ollinger G, Colgate JE, Peshkin MA, Goswami A. *IEEE 10th International Conference on Active-Impedance Control of a Lower-Limb Assistive Exoskeleton. Rehabilitation Robotics*, Noordwijk, Netherlands, 2007.

Bays PM, Flanagan JR, Wolpert DM. Interference between velocity-dependent and position-dependent force-fields indicates that tasks depending on different kinematic parameters compete for motor working memory. *Exp Brain Res* 163: 400–405, 2005.

Brashers-Krug T, Shadmehr R, Bizzi E. Consolidation in human motor memory. *Nature* 382: 252–255, 1996.

Burdet E, Osu R, Franklin DW, Milner TE, Kawato M. The central nervous system stabilizes unstable dynamics by learning optimal impedance. *Nature* 414: 446–449, 2001.

Conditt MA, Mussa-Ivaldi FA. Central representation of time during motor learning. *Proc Natl Acad Sci USA* 96: 11625–11630, 1999.

Davidson PR, Wolpert DM. Internal models underlying grasp can be additively combined. *Exp Brain Res* 155: 334–340, 2004.

Emken JL, Benitez R, Beinkensmeyer DJ. Human-robot cooperative movement training: learning a novel sensory motor transformation during walking with robotic assistance-as-needed. *J Neuroeng Rehabil* 4: 8, 2007.

Emken JL, Reinkensmeyer DJ. Robot-enhanced motor learning: accelerating internal model formation during locomotion by transient dynamic amplification. *IEEE Trans Neural Syst Rehabil Eng* 13: 33–39, 2005.

Flanagan JR, Lolley S. The inertial anisotropy of the arm is accurately predicted during movement planning. *J Neurosci* 21: 1361–1369, 2001.

Franklin DW, Liaw G, Milner TE, Osu R, Burdet E, Kawato M. Endpoint stiffness of the arm is directionally tuned to instability in the environment. *J Neurosci* 27: 7705–7716, 2007.

Gandolfo F, Mussa-Ivaldi FA, Bizzi E. Motor learning by field approximation. *Proc Natl Acad Sci USA* 93: 3843–3846, 1996.

Gentili R, Cahouet V, Ballay Y, Papaxanthis C. Inertial properties of the arm are accurately predicted during motor imagery. *Behav Brain Res* 155: 231–239, 2004.

Ghahramani Z, Wolpert DM. Modular decomposition in visuomotor learning. *Nature* 386: 392–395, 1997.

Giuffrida CG, Shea JB, Fairbrother JT. Differential transfer benefits of increased practice for constant, blocked, and serial practice schedules. *J Mot Behav* 34: 353–365, 2002.

Held R, Rekosh J. Motor-sensory feedback and the geometry of visual space. *Science* 141: 722–723, 1963.

Hinder MR, Walk L. The interference effects of non-rotated versus counter-rotated trials in visuomotor adaptation. *Exp Brain Res* 180: 629–640, 2007.

Hogan N. Impedance control—an approach to manipulation. I. Theory. II. Implementation. III. Applications. *ASME Trans J Dynam Syst Measurement Control B* 107: 1–24, 1985.

Housman SJ, Scott KM, Reinkensmeyer DJ. A randomized controlled trial of gravity-supported, computer-enhanced arm exercise for individuals with severe hemiparesis. *Neurorehabil Neural Repair* 23: 505–514, 2009.

Huang FC, Gillespie RB, Kuo AD. Human adaptation to interaction forces in visuo-motor coordination. *IEEE Trans Neural Syst Rehabil Eng* 14: 390–397, 2006.

Huang FC, Gillespie RB, Kuo AD. Visual and haptic feedback contribute to tuning and online control during object manipulation. *J Mot Behav* 39: 179–193, 2007.

Imamizu H, Higuchi S, Toda A, Kawato M. Reorganization of brain activity for multiple internal models after short but intensive training. *Cortex* 43: 338–349, 2007.

Johnson MJ, Van der Loos HF, Burgar CG, Shor P, Leifer LJ. Experimental results using force-feedback cueing in robot-assisted stroke therapy. *IEEE Trans Neural Syst Rehabil Eng* 13: 335–348, 2005.

Kahn LE, Zygman ML, Rymer WZ, Reinkensmeyer DJ. Robot-assisted reaching exercise promotes arm movement recovery in chronic hemiparetic stroke: a randomized controlled pilot study. *J Neuroeng Rehabil* 3: 12, 2006.

Karniel A, Mussa-Ivaldi FA. Sequence, time, or state representation: how does the motor control system adapt to variable environments? *Biol Cybern* 89: 10–21, 2003.

Kawato M. Internal models for motor control and trajectory planning. *Curr Opin Neurobiol* 9: 718–727, 1999.

Kazerooni H. The human power amplifier technology at the University of California, Berkeley. *Robot Auton Syst* 19: 179–187, 1996.

Krakauer JW, Ghilardi MF, Ghez C. Independent learning of internal models for kinematic and dynamic control of reaching. *Nat Neurosci* 2: 1026–1031, 1999.

Krakauer JW, Mazzoni P, Ghazizadeh A, Ravindran R, Shadmehr R. Generalization of motor learning depends on the history of prior action. *PLoS Biol* 4: 1798–1808, 2006.

Krebs HI, Palazzolo J, Dipietro L, Ferraro M, Krol J, Rannekleiv K, Volpe BT, Hogan N. Rehabilitation robotics: performance-based progressive robot-assisted therapy. *Auton Robots* 15: 7–20, 2003.

Kreifeldt JG, Chuang MC. Moment of inertia: psychophysical study of an overlooked sensation. *Science* 206: 588–590, 1979.

Krouchev NI, Kalaska JF. Context-dependent anticipation of different task dynamics: rapid recall of appropriate motor skills using visual cues. *J Neurophysiol* 89: 1165–1175, 2003.

Ljung L. *System Identification: Theory for the User*. Upper Saddle River, NJ: Prentice Hall, 1999.

Mah CD, Mussa-Ivaldi FA. Evidence for a specific internal representation of motion-force relationships during object manipulation. *Biol Cybern* 88: 60–72, 2003.

Matsuoka Y, Brewer BR, Klatzky RL. Using visual feedback distortion to alter coordinated pinching patterns for robotic rehabilitation. *J Neuroeng Rehabil* 4: 17, 2007.

McIntyre, J, Lipshits M, Zaoui M, Berthoz A, Gurfinkel V. Internal reference frames for representation and storage of visual information: the role of gravity. *Acta Astronaut* 49: 111–121, 2001.

Milner TE. Adaptation to destabilizing dynamics by means of muscle cocontraction. *Exp Brain Res* 143: 406–416, 2002.

Milner TE. Accuracy of internal dynamics models in limb movements depends on stability. *Exp Brain Res* 159: 172–184, 2004.

Milner TE, Cloutier C. Compensation for mechanically unstable loading in voluntary wrist movement. *Exp Brain Res* 94: 522–532, 1993.

Milner TE, Cloutier C. Damping of the wrist joint during voluntary movement. *Exp Brain Res* 122: 309–317, 1998.

Patton JL, Kovic M, Mussa-Ivaldi FA. Custom-designed haptic training for restoring reaching ability to individuals with poststroke hemiparesis. *J Rehabil Res Dev* 43: 643–656, 2006.

Patton JL, Mussa-Ivaldi FA. Robot-assisted adaptive training: custom force fields for teaching movement patterns. *IEEE Trans Biomed Eng* 51: 636–646, 2004.

Piccoli B, Kulkarni J. Pumping a swing by standing and squatting: do children pump time optimally? *IEEE Control Syst Magazine* 25: 48–56, 2005.

Sabes PN, Jordan ML, Wolpert DM. The role of inertial sensitivity in motor planning. *J Neurosci* 18: 5948–5957, 1998.

Salimi I, Hollender I, Frazier W, Gordon AM. Specificity of internal representations underlying grasping. *J Neurophysiol* 84: 2390–2397, 2000.

Sanchez RJ, Liu J, Rao S, Shah P, Smith R, Rahman T, Cramer SC, Bobrow JE, Reinkensmeyer DJ. Automating arm movement training following severe stroke: functional exercises with quantitative feedback in a gravity-reduced environment. *IEEE Trans Neural Syst Rehabil Eng* 14: 378–389, 2006.

Schaal S, Atkeson CG, Sternad D. One-handed juggling: a dynamical approach to a rhythmic movement task. *J Mot Behav* 28: 165–183, 1996.

Shadmehr R, Mussa-Ivaldi FA. Adaptive representation of dynamics during learning of a motor task. *J Neurosci* 14: 3208–3224, 1994

Shea CH, Lai Q, Wright DL, Immink M, Black C. Consistent and variable practice conditions: effects on relative and absolute timing. *J Mot Behav* 33: 139–152, 2001.

Shoenfelt EL, Snyder LA, Maue AE, McDowell CP, Woolard CD. Comparison of constant and variable practice conditions on free-throw shooting. *Percept Mot Skills* 94: 1113–1123, 2002.

Solomon HY, Turvey MT, Burton G. Perceiving extents of rods by wielding: haptic diagonalization and decomposition of the inertia tensor. *J Exp Psychol Hum Percept Perform* 15: 58–68, 1989.

Sveistrup H. Motor rehabilitation using virtual reality. *J Neuroeng Rehabil* 1: 10, 2004.

Takahashi CD, Scheidt RA, Reinkensmeyer DJ. Impedance control and internal model formation when reaching in a randomly varying dynamical environment. *J Neurophysiol* 86: 1047–1051, 2001.

Todorov E, Shadmehr R, Bizzi E. Augmented feedback presented in a virtual environment accelerates learning of a difficult motor task. *J Mot Behav* 29: 147–158, 1997.

Tong C, Wolpert DM, Flanagan JR. Kinematics and dynamics are not represented independently in motor working memory: evidence from an interference study. *J Neurosci* 22: 1108–1113, 2002.

Wei Y, Bajaj P, Scheidt R, Patton J. Visual error augmentation for enhancing motor learning and rehabilitative relearning. *ICORR 2005 9th International Conference on Rehabilitation Robotics*.

Wei Y, Patton JL. Force field training to facilitate learning visual distortions: a "sensory crossover" experiment. *Proceedings of the 12th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, Chicago, IL, 2004.