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Haptic Identification of Surfaces as Fields of Force

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Chib, Vikram S., James L. Patton, Kevin M. Lynch, and Ferdinando A. Mussa-Ivaldi. Haptic identification of surfaces as fields of force. *J Neurophysiol* 95: 1068–1077, 2006. First published October 5, 2005; doi:10.1152/jn.00610.2005. The ability to discriminate an object's shape and mechanical properties from touch is one of the most fundamental somatosensory functions. When exploring physical properties of an object, such as stiffness and curvature, humans probe the object's surface and obtain information from the many sensory receptors in their upper limbs. This sensory information is critical for the guidance of actions. We studied how humans acquire an internal representation of the shape and mechanical properties of surfaces and how this information affects the execution of trajectories over the surface. Experiments involved subjects executing trajectories while holding a planar manipulandum that renders planar virtual objects with variable shape and mechanical properties. Subjects were instructed to make reaching movements with the hand between points on the boundary of a curved virtual disk of varying stiffness and curvature. The results suggest two classifications of adaptive responses: force perturbations and object boundaries. In the first case, a rectilinear hand movement is enforced by opposing the interaction forces. In the second case, the trajectory conforms to the object boundary so as to reduce interaction forces. While this dichotomy is evident for very rigid and very soft objects, the likelihood of an object boundary classification depended, in a smooth and monotonic way, on the average force experienced during the initial movements. Furthermore, the observed response across a variety of stiffness values lead to a constant average interaction force after adaptation. This suggests that the nervous system may select from the two responses through a mechanism that attempts to establish a constant interaction force.

INTRODUCTION

Studies have been performed to understand how humans perceive shape through active touch. Kappers et al. (1994) found that we are capable of learning and distinguishing slight differences in the curvature of various surfaces. Further study of actively touched curved surfaces has shown that adaptation and after effects are present after haptic exploration (Vogels et al. 1996). These after effects are manifested as flat surfaces being judged as convex after touching of a concave surface and flat surfaces being judged as concave after touching of a convex surface. Haptic after effects increase with the time of contact with the curved surface and decrease with the time elapsed between the touching of two different surfaces (Vogels et al. 2001).

The stiffness, or degree of rigidity, of an object is critically important for manipulation. Psychophysical studies have been performed to determine thresholds for stiffness discrimination (Jones and Hunter 1990). These studies used a contralateral

limb matching procedure, in which subjects adjusted the stiffness of a motor connected to one arm until it was perceived to be the same as that connected to the other arm. These studies concluded that the sensitivity of stiffness discrimination was much worse than would be expected by combining the sensitivities for force and displacement discrimination.

Rigid objects, such as walls and table tops, are characterized by high-impedance boundaries. When the hand comes in contact with these objects, there is minimal or negligible penetration inside the boundary, regardless of the force applied to the object boundary. Other objects, such as pillows and computer keyboards, respond to applied forces with larger displacements. In mechanical terms, these different behaviors are captured by describing objects as *fields* of position-dependent forces. Stiffness is the factor that characterizes how an object responds to a given displacement at its surface. In this study, we investigate interactions between the hand and objects as interactions of the hand with external force fields.

Unperturbed free reaching movements have been studied extensively (Flash and Hogan 1985; Hogan 1984; Morasso 1981). More recently, there has been a growing body of investigation concerning the effect of deterministic force fields on free reaching movements of the arm (Flash and Gurevich 1992; Gandolfo et al. 1996; Matsuoka 1998; Shadmehr and Mussa-Ivaldi 1994; Thoroughman and Shadmehr 2000). However, the idea of using similar experimental paradigms for studying the interaction with object boundaries has not yet been explored. Studies of free reaching movements in a field of forces have highlighted the existence of adaptive mechanisms that tend to restore straight-line movements and the kinematics of the unperturbed hand motion. This makes sense if one indeed considers the external forces as a perturbation to be rejected. However, the same mechanism would not be appropriate when the hand encounters an unexpected hard surface in a dark room. In this case, "fighting the field" would be pointless and painful. One would rather comply and modify the trajectory to avoid the wall or to move smoothly over its surface. While these considerations are self-evident, a question arises as to what mechanical conditions would lead the motor system to react to a force field as a disturbance to overcome or as a boundary to comply with. Here, we address this question together with some corollary issues. Is the dichotomy between the representation of fields as disturbances or boundaries the outcome of an adaptive process? Is the dichotomy itself characterized by a sharp, "two state" transition, like the Necker-cube illusion and other perceptual dichotomies? Is there a

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critical value in the local variation of the force field (i.e., the “stiffness”) that the motor system uses to discriminate boundaries from disturbances? We have addressed these questions by observing the effect on hand movements of force fields that emulated a circular planar object of variable stiffness and curvature.

Our findings show the existence of both compensatory and compliant responses occurring at different values of surface stiffness. The lowest values of stiffness lead to compensatory responses in which a free space trajectory is recovered, whereas the highest values lead to compliant responses. However, the experiments also revealed a continuum of motor responses, rather than a sharp transition. A smooth transition from compensation to compliance appeared across a continuum of stiffness levels. Objects with different stiffness induced, as expected, different levels of interaction forces. However, a striking effect of practice was a strong tendency toward a fixed average interaction force that did not depend on the object’s stiffness. Thus we observed either compensatory responses or compliant adaptive responses depending on the relation of the initial interaction force to this final fixed level of interaction force. Taken together, these studies reveal a mechanism of adaptation that may subserve the implicit learning of object shapes through repeated mechanical interactions.

METHODS

Experimental apparatus

Experiments were performed using a two-degrees-of-freedom planar manipulandum as seen in Fig. 1. Subjects made goal-directed movements in the plane of the manipulandum while grasping its handle. The manipulandum was similar to those previously described (Mussa-Ivaldi and Bizzi 2000; Shadmehr and Mussa-Ivaldi 1994). It

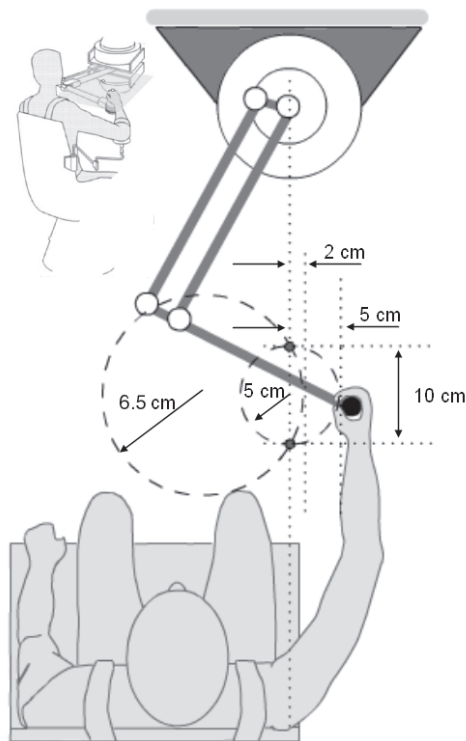


FIG. 1. Schematic of manipulandum and dimensions of the position-dependent force fields.

was instrumented with joint encoders that report the joint angles at a frequency of 100 Hz. Position and velocity of the manipulandum handle were computed from these encoder signals. The manipulandum was also equipped with two torque motors that generated the force fields corresponding to the virtual object. Endpoint forces were acquired using a six-degrees-of-freedom load cell fixed to the handle of the robot. Visual feedback was given to subjects through a projection system. This system displayed a cursor registered to the movement of the manipulandum handle, as well as start and goal positions, to prompt subjects’ movements. The cursor and visual cues were presented through an LCD projector projecting on a horizontal plane. Vision of the subjects’ arm was obscured by the projection plane.

Force fields

The force fields experienced by subjects were computed in real time using the formula

$$f = \begin{cases} K(R - r) + br & r \leq R \\ 0 & r > R \end{cases} \quad (1)$$

This expression defines a circular, viscoelastic force field in polar coordinates; where f is the magnitude of interface force produced by the robot, R is the radius of the virtual disk, r is the distance of the handle from the center of the disk, K is a spring constant, and b is a damping constant. The interface force is always directed radially away from the center of the disk. Damping is added to alleviate instabilities encountered at higher stiffnesses.

Subjects

Twenty-two naive, healthy, volunteers (age range, 18–35 yr) participated in this study after giving informed consent in accordance with the standards of the Institutional Review Board of Northwestern University. All subjects were right-handed and had normal vision or vision that was corrected to normal. Subjects were divided into two groups. The first experimental group (low-curvature group), consisting of nine subjects, was prompted to make reaching movements in the presence of a virtual surface of curvature 15 m^{-1} ($R = 6.5 \text{ cm}$). The second group of nine subjects (high-curvature group) was prompted to make movements in the presence of a virtual surface of curvature 20 m^{-1} ($R = 5.0 \text{ cm}$). To evaluate memory effects related to order of stiffness presentation, a group of four subjects was used (memory effect group). These subjects were presented surfaces in order of descending stiffness, as opposed to ascending order of stiffness presentation in the case of the low- and high-curvature groups.

Experimental protocol

Subjects made goal-directed reaching movements from a start target to a goal target. Their arms were supported against gravity and constrained to the plane of movement of the manipulandum by a low-inertia arm support. During a trial, a target was projected onto the subject’s workspace, and the subject was asked to make one continuous movement to place a cursor registered to the manipulandum handle within the target, while achieving a desired maximum velocity. The next target appeared after the subject held the cursor at the prior target for 1 s. Subjects were given feedback as to whether they moved faster or slower than the desired maximum velocity. The optimal speed of movement was specified before each experiment. When subjects achieved a maximum velocity $>5\%$ faster than the desired velocity, the target turned green. If the target was reached with a maximum velocity $>5\%$ slower than the desired velocity, the target turned blue. When the target was reached within the desired maximum velocity range, the target was animated to “explode,” and a distinctive sound was presented to reinforce the perception of a successful

movement. These feedback cues allowed subjects to achieve a consistent maximum speed of movement.

Before the introduction of force fields, subjects practiced making point-to-point movements under the required velocity constraints, in the absence of a virtual object, for 60 movements. To assess the typical performance of subject, undisturbed in free space, objects were not introduced during this baseline unperturbed phase. This phase of the experiment allowed subjects to familiarize themselves with the passive dynamics of the manipulandum.

After the baseline unperturbed phase, virtual objects were presented to the subject. Subjects were only provided with a haptic rendering of the virtual object; visual information regarding the geometry of the object was not presented. The dimensions of the virtual objects are shown schematically in Fig. 1. A testing phase consisted of the subject moving between targets located on the boundary of the virtual object. Subjects made 100 reaching movements between the presented start and goal positions. The first 50 movements of a testing phase served as a practice period for the subject to acquire information about the virtual surface. During the final 50 movements of the testing phase, catch trials—movements during which, unexpectedly, no force field was present—were introduced pseudorandomly for 12.5% of the movements. These catch trials were introduced to reveal any adaptations of the feedforward motor command that may have occurred after training with the virtual object (Shadmehr and Mussa-Ivaldi 1994).

After completion of the phase consisting of 100 movements with the virtual object, a “wash-out” phase, consisting of 50 movements in a null field, was introduced. This phase allowed for deadadaptation and unlearning of the field encountered during the previous phase. Six different stiffness levels were tested ($K = 200, 400, 800, 1,200, 1,600, 2,000$ N/m). The stiffness levels were presented in order of increasing magnitude. One group of subjects (low-curvature group) was exposed to the various stiffness levels with a virtual disk of curvature 15 m^{-1} ($R = 6.5\text{ cm}$), whereas a second group (high-curvature group) was exposed to the same stiffness levels with a virtual disk of curvature 20 m^{-1} ($R = 5\text{ cm}$). The experimental protocol and instructions were exactly the same for both groups; the only difference between the experiments was the curvature of the fields presented to subjects.

Field stiffness was presented in ascending order after preliminary studies showed a marked memory effect when surfaces of high stiffness were presented before those of lower stiffness. When subjects were presented with a high stiffness field that clearly revealed the shape of the boundary, they showed a marked tendency to identify the boundaries of subsequent low stiffness fields. That is, the identification of a rigid boundary tended to persist in lower stiffness fields. This finding is presented at the end of RESULTS. Because the main interest of this study was to find the minimum stiffness that would lead to identification of a boundary and to determine whether such a value has the property of a threshold leading to an abrupt change in behavior, we gradually increased the presented stiffness levels in search of such a threshold.

Trajectory analysis

Two different measures were used to quantify subjects' response to virtual objects and their subsequent learning.

AREA REACHING DEVIATION. The measure of area reaching deviation (ARD) was used to evaluate a subjects' deviation from a straight line path. This measure was defined as the signed area between the trial path and a reference straight-line path between the start and goal positions. Paths to the right of the reference straight-line path yielded positive ARD, whereas those to the left yield negative ARD. If the trajectory is monotonic in y , the signed area reaching deviation can be computed by

$$A = \int_{y_i}^{y_f} x\ dy \quad (2)$$

AVERAGE INTERFACE FORCE. The measure of interface force was used to evaluate the forces imposed by the virtual object during subjects' movements. Force measures were calculated using subjects' position and velocity signals and Eq. 1. The calculated force values were integrated over the duration of the movement to acquire a resulting force cost (Eq. 3) for an entire reaching movement. This measure expresses the forces imposed by the environment and not the forces produced by the subject

$$F = \frac{\int_{t_i}^{t_f} \|f\| dt}{t_f - t_i} \quad (3)$$

Psychometric function

A common means of quantifying a subject's performance of a psychophysical task is the fitting of a psychometric function (Wichmann and Hill 2001a). The psychometric function relates an observer's performance of a psychophysical task to some physical aspect of stimulus. For these experiments, the performance metric used was the sign of the ARD. A two-alternative paradigm was implemented for the catch trials performed at each stiffness level. Catch trials having a negative ARD were classified as perception of a field, whereas those having a positive ARD were classified as perception of an object boundary or surface. Subjects' results were compiled into a single group measure for each stiffness level. This measure was expressed as the proportion of positive surface responses at each stiffness level.

The general form of the psychometric function is

$$\psi(x, \alpha, \beta, \gamma, \lambda) = \gamma + (1 - \gamma - \lambda)F(x; \alpha, \beta) \quad (4)$$

The shape of the curve is determined by the parameters (α, β, λ) and the choice of a two-parameter function F , which is typically a sigmoid function. For these experiments, a cumulative Gaussian was used for F . From the defined range, it follows that the parameter γ gives the lower bound of x , which can be interpreted as the base rate of performance in the absence of a signal. The upper bound of the curve, the performance level for an arbitrarily large stimulus level, is given as $1 - \lambda$. For these experiments, $\lambda = 0$, because it was found that as stiffness increased subjects had a greater propensity to discriminate a surface. Between the two bounds, the shape of the curve is determined by α and β .

Bootstrapping was used to generate 95% CIs for the resulting psychometric functions. These CIs represent the variability in subjects' probability of perceiving a surface given the independent variable of surface stiffness. The bootstrap method is a Monte Carlo resampling technique relying on a large number of simulated repetitions of the original experiment. Simulated repetitions of the experiment are obtained by repetitively resampling subsamples of the data. Bootstrap methods are especially well suited for analysis of psychophysical data because their accuracy does not rely on a large number or trials, as do methods from conventional statistical asymptotic theory (Wichmann and Hill 2001b). To construct 95% CIs for psychometric functions obtained during this study, random combinations of subject's psychometric functions were sampled with replacement 1,000 times.

RESULTS

Adaptation to virtual objects of varying stiffness

A typical set of movement trajectories for a subject in the low-curvature group, with different field stiffness and at different stages of learning (early exposure, mid exposure, and late exposure), is shown in Fig. 2. At all levels of stiffness, during the early exposure phase, the effect of the virtual object

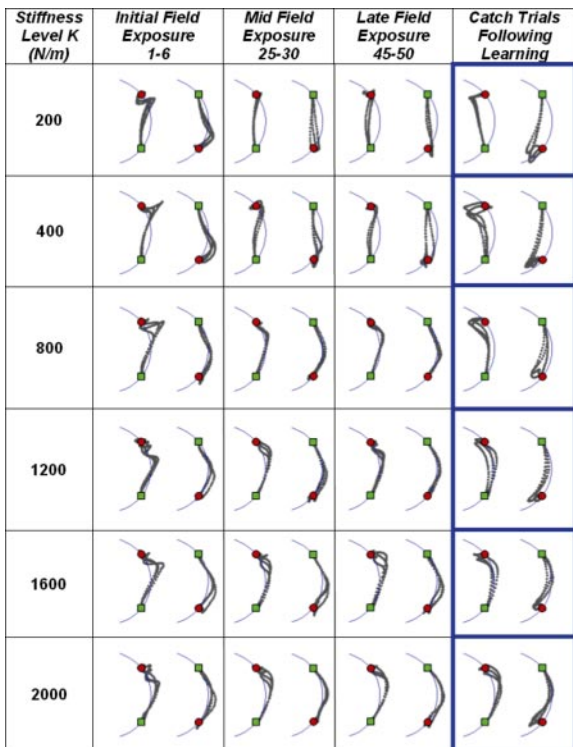


FIG. 2. Low-curvature group trajectories. The 1st 6 trajectories from various stages of adaptation for a representative subject. Green squares represent the start position; red circles represent the goal position.

on the hand trajectory was quite significant. The time-course of movements during the early exposure phase can be divided into two parts. During the first part, the hand was driven off course by the field and forced away from a straight-line trajectory. During the second part of the movement, after the force field of the virtual object had caused the hand to veer off course from the target, subjects made a second movement back toward the target. At low stiffness values (200 and 400 N/m), after adaptation, subjects produced straight-line movements through the field (Fig. 2).

Repeated practice of movements with high-stiffness virtual disks ($K = 800, 1,200, 1,600,$ and $2,000$ N/m) resulted in a markedly different adaptation. As with low stiffness disks, initial exposure to the field resulted in a two-segment movement, with the first portion corresponding to the hand being perturbed by the force field and forced away from the boundary of the virtual object and the second portion corresponding to a recovery to the goal position (Fig. 2). This qualitative pattern of initial responses was remarkably similar at all field strengths. However, unlike adaptation to low stiffness fields, adaptation to high stiffness fields did not result in subjects recovering straight-line movements. During mid and late ex-

posure, subjects produced movements that followed the virtual surface.

Data from the washout periods after force field learning indicate that the effects of force field adaptation were completely suppressed by the end of the 50 trial washout periods (Fig. 3). Washout blocks were presented between the presentations of fields of different stiffness. During washout blocks, subjects' level of ARD converged to zero, which is consistent with the production of straight line trajectories after movements in the null field. This finding does not exclude the possibility that subjects maintained some memory trace of earlier exposure and that this memory effect could lead to a slowly changing perception of stiffness. Furthermore, even a more prolonged period of rest would not be adequate to extinguish that effect, because some memory of experienced force fields have been documented to persist for weeks (Shadmehr and Brashers-Krug 1997). However, if present, this memory did not have an impact on the baseline movements before each block of trials.

These qualitative observations of subjects' adaptations to virtual objects of varying stiffness are quantified and summarized for all subjects in Fig. 4A. As previously described, with low stiffness values (200 and 400 N/m), after adaptation, subjects produced straight-line movements through the field (Fig. 2). This result was captured by the ARD before and at the end of practice. ARD measures the area spanned by a subject's deviation from a straight path (see METHODS). ARD for virtual surfaces of 200 and 400 N/m were significantly different ($P < 0.05$; Fig. 4A). At these low-stiffness values, ARD was reduced to nearly zero, indicating that subjects attempted—and succeeded—to produce straight-line movements. At the high stiffness levels, ARD was not significantly reduced after learning. The data in Fig. 4A show that the measure of ARD increases as the stiffness level increases. Thus as stiffness is increased, subjects began to produce trajectories that conformed to the boundary of the virtual object, as opposed to actively counteracting the forces generated by the virtual object.

The shapes of the adapted trajectories varied with the levels of stiffness (Fig. 2, late field exposure). This was also reflected by the pattern of ARD (Fig. 4A). However, a unifying feature among the adapted movements is the average interface force. Through the continuum of stiffness levels, subjects tended to produce similar average interface forces after adaptation (Fig. 4B). A two-factor ANOVA did not find a significant difference among average interface force for the six stiffness levels for subjects in the low-curvature group after adaptation had occurred ($F_{6,5} = 0.187$; $P = 0.966$).

After effects from adaptation to the low-stiffness field were observed during catch trials at the end on training. During catch trials, the virtual disk was unexpectedly removed from the path, and subjects made movements in an unperturbed environment. These after effects are mirror images of the

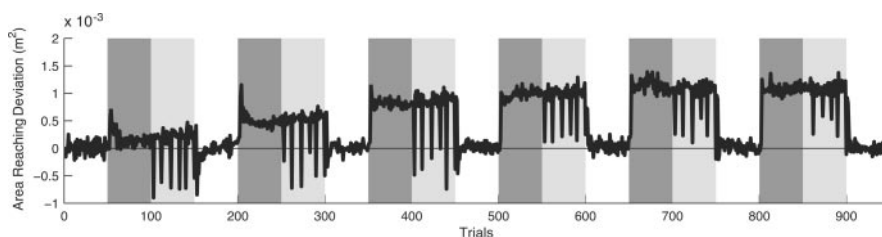


FIG. 3. Learning curve for the low-curvature group. White blocks represent null field presentation, dark gray blocks represent force field presentation, and light gray blocks represent a phase of pseudorandom catch trials.

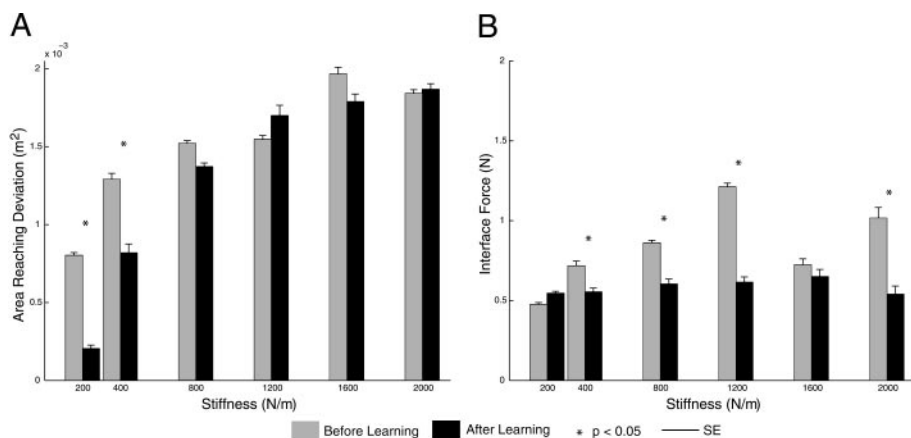


FIG. 4. Learning data for the low-curvature group. Measures shown are an average of the 1st and last 5 trials averaged across all subjects. A: area reaching deviation (ARD). B: interface force.

responses to the initial field exposure (Fig. 2). This suggests that, in the presence of low-stiffness position-dependent force fields, subjects adapted by developing an internal representation of the field. The internal representation predicted and canceled the forces of the virtual disk. At higher stiffness levels, this was not the case. Once a stiffness threshold was exceeded, subjects' after effects appeared in the direction of the applied forces and following the profile of the virtual surface. The amount by which the after effects appeared in the direction of the applied forces of the virtual surface and away from a straight line trajectory increased as the stiffness of the surface increased.

Group results of ARD for catch trials showed a gradual transition between negative after effects at low stiffness, which indicates that subjects produced a compensatory response opposing the forces associated with the virtual disk, and positive after effects at high stiffness, which indicates that subjects produced a response conforming to the boundary of the virtual surface (Fig. 5A). We used the measure of ARD to derive a binary classification of force fields as either objects or disturbances. Specifically, we used catch trials leading to a positive ARD to classify subjects' perception of a virtual disk of a given stiffness as being a surface. This allowed us to fit a psychometric function to the response (Fig. 5B). The psychometric function, consistent with the underlying set of ARDs, showed a smooth pattern of classification across stiffness levels. The

probability of perceiving the field as an object boundary, or surface, progressively increased as the level of stiffness increased, reaching chance (0.5) in the stiffness range of 1,000–1,300 N/m.

Influence of surface curvature

To assess the effect surface curvature has on the adaptive interaction with an object, an additional subject group engaged in the previously described experimental protocol. This group, the high-curvature group, interacted with a virtual surface of increased curvature (20 m^{-1}).

For the high-curvature group, we did not observe force field adaptation with recovery of straight-line movements at low stiffness values. Instead, after training with the low stiffness surface, subjects exhibited movements that complied with and conformed to the circular disk boundary (Fig. 6). This result was manifested in subjects catch trial movements. During these movements, subjects increased ARD at lower stiffness levels after learning (Fig. 7A). Furthermore, after effects from this higher curvature level remained positive and gradually increased across all stiffness levels, indicating that subjects produced after effects in the direction of the applied forces and approximately conforming to the profile of the virtual boundary. The high-curvature group showed a monotonic increase of ARD for catch trials (Fig. 8A) and probability of perceiving a

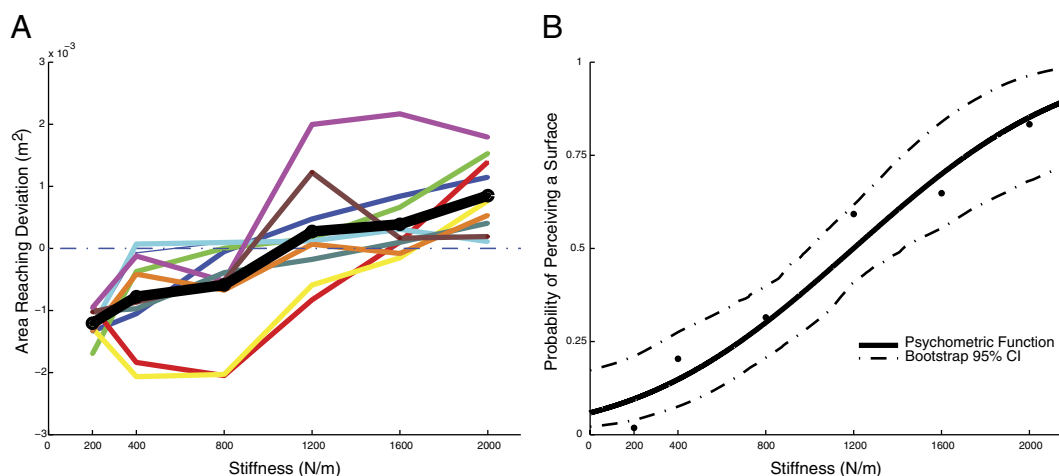


FIG. 5. Low-curvature group catch trial data and psychometric function. A: ARD for catch trials of subjects interacting with a surface of curvature 15 m^{-1} . Colored lines are data from a single subject; bold black line is a group average. B: psychometric function computed for all subjects.

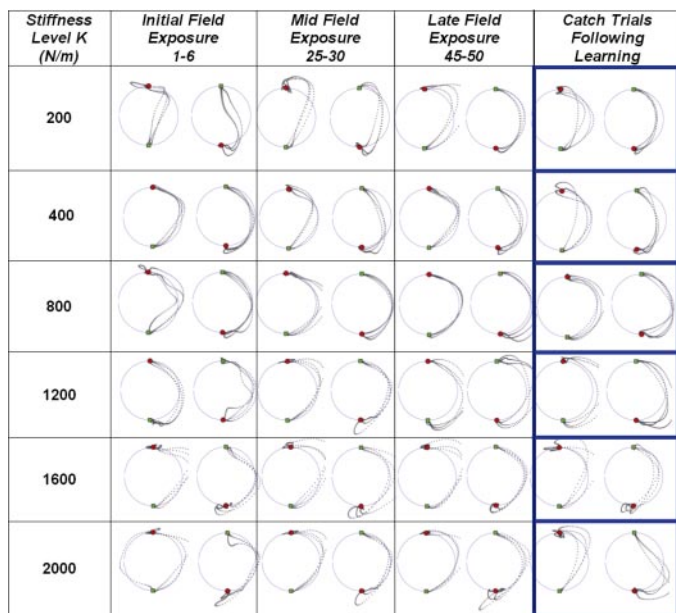


FIG. 6. High-curvature group trajectories. The 1st 6 trajectories from various stages of adaptation for a representative subject. Green squares represent the start position; red circles represent the goal position.

surface as a boundary (Fig. 8B) as the stiffness level of the virtual surface increased. Again, the learning curves from this protocol show after-effect washout after 50 movements in a null field (Fig. 9).

As in the case of the surface experienced by the low-curvature group, the learned behavior followed a gradual trend across stiffness levels. Another common feature between the adaptations to fields of different curvatures was the average interface force experienced after learning. Results showed that, in the case of the higher curvature surface, subjects again achieved an invariant level of interface force (Fig. 9B). While the level of force was larger than that found for the low-curvature group, it remained relatively constant across all stiffness levels. A two-factor ANOVA without replication did not find a significant difference among the six stiffness levels ($F_{6,5} = 1.272$; $P = 0.307$) after learning. For both groups, high curvature and low curvature, the relative excursion of average interface force was smaller than the excursion in the kinematic

measure of ARD. This result suggests that an intended interface force is being regulated by the control system during haptic exploration.

Regulation of average interface force

Our findings suggest that the unifying theme across these stiffness and curvature levels was a subject's tendency to generate a constant level of interface force regardless of object mechanics. A regression of interface force before learning versus ARD after learning (Fig. 10A) showed very similar trends in both curvature groups. It is important to note that the forces presented in these regressions are those produced solely by the environment and do not include forces generated by the subject. Considering the similarity in these regressions, we are led to consider a single model to describe the experimental data. Indeed, using a single model to account for the data is consistent with the more general Occam's razor principle of minimizing the number of parameters (i.e., the complexity of the model or the "size" of the hypothesis space) needed to account for the data. This single model suggests the existence of a common adaptation strategy for the low-curvature and high-curvature groups, whose outcome depends on the amount of interface force experienced in the early interactions with the field/surface. Accordingly, the level of initial interface force experienced may be the key factor in subjects' perception of a field as a surface. A gradual trend was seen between subjects' level of interface force before learning and their probability of perceiving a surface (Fig. 10B). The threshold of preadaptation interface force at which subjects began to perceive surfaces greater than chance occurs at ~ 1.0 N. The fact that interface force, rather than stiffness or curvature, is the best predictor of the final classification suggests (see DISCUSSION) that the feed-forward command plays a central role in haptic perception.

Responses to decreasing stiffness: a memory effect

We found a strong memory effect when surfaces of high stiffness were presented before those of lower stiffness. Four subjects were presented with field stiffness in descending order and were asked to execute the reaching task in the presence of a field with the same geometry as presented to the low-

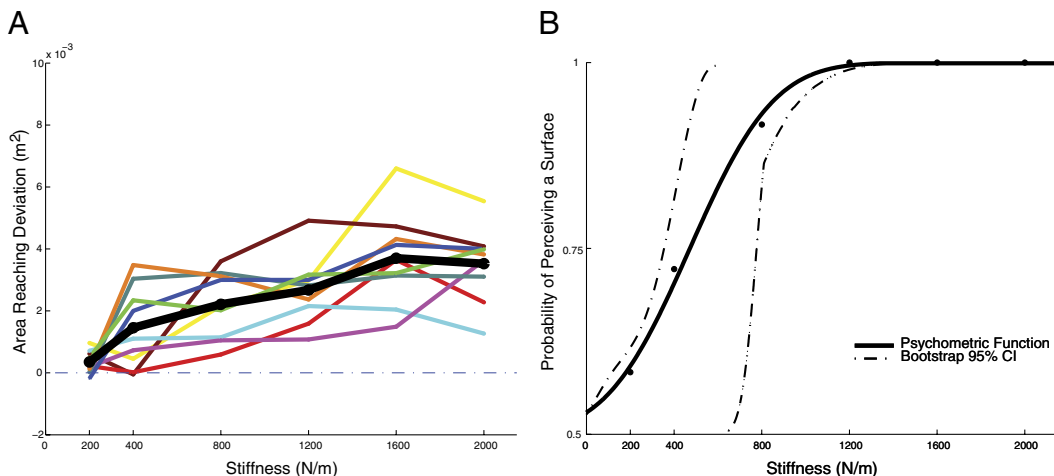


FIG. 7. High-curvature group catch trial data and psychometric function. A: ARD for catch trials of subjects interacting with a surface of curvature 20 m^{-1} . Colored lines are data from a single subject; bold black line is a group average. B: a psychometric function computed for all subjects.

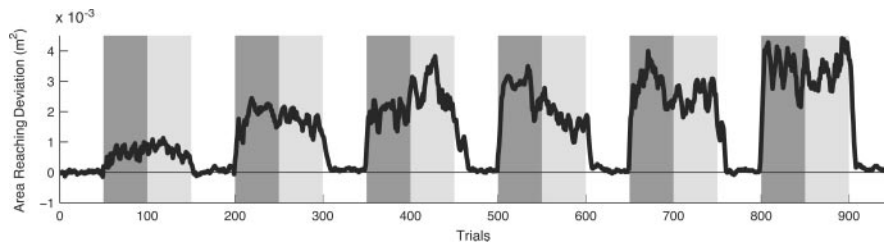


FIG. 8. Learning curve for the high-curvature group. White blocks represent null field presentation, dark gray blocks represent force field presentation, and light gray blocks represent a phase of pseudorandom catch trials.

curvature group. We observed that, as the stiffness of the field was reduced, starting from a level that clearly revealed the shape of the boundary, subjects had a marked tendency to move along the boundaries of subsequent low stiffness surfaces. Thus the identification of a rigid boundary persisted in lower stiffness fields. The data in Fig. 11 show ARD for catch trials from these subjects. It is apparent that the after effects were in the direction of the boundary (i.e., positive ARD) even at the lowest stiffness values, suggesting that subjects were biased by their initial perception of surface boundaries during initial high stiffness interactions. This is clearly in contrast with the trend shown in Fig. 5A. Because of this memory effect, we decided to present the subsequent boundaries in ascending order, which would have allowed us to detect a transition in behavior if a critical value of stiffness delimited the classification of a force field as either a disturbance or an object.

DISCUSSION

We found that the adaptation of movements to a virtual surface is dependent on both surface stiffness and surface curvature. For a given surface curvature, when subjects exceed a threshold stiffness level, they learned to produce a smooth trajectory on the boundary of the surface. In contrast, at lower stiffness, they adapted by recovering the unperturbed kinematics of hand movements in free space. While these distinctly different adaptation strategies were clearly evident at the extremes of tested stiffness, we did not observe a distinct dichotomy but a smooth transition through a continuum of stiffness levels. Furthermore, across these stiffness levels subjects produced an invariant level of average interface force, suggesting a common underlying strategy of interaction.

At the lowest stiffness (200 N/m) and low curvature, subjects produced a higher average interface force after adaptation compared with interface forces observed before adaptation

(Fig. 4B). Furthermore, at low stiffness levels (200 and 400 N/m), we found a significant reduction in lateral deviation after practice. The same subjects generated after effects with deviation opposite to the direction of the force. This is consistent with the hypothesis that, at low stiffness and curvature, subjects developed an internal representation of the forces generated by the virtual object. This result is in holding with observations from previous force field adaptation experiments, where the ability to recover a straight-line movement after adaptation was considered to result from an internal model of the perturbing field (Shadmehr and Mussa-Ivaldi 1994; Thoroughman and Shadmehr 2000).

At the higher stiffness and curvature levels, subjects abandoned the goal of reducing straight line deviations. Instead, they reduced the interface force by complying with the shape of the object boundary. This trend is shown by increases in lateral deviation and reductions in interface force after learning. This suggests that, at high stiffness, subjects formed an internal representation of the virtual surface based on the reduction of the interface force to a given level.

After effects from catch trials at higher stiffness levels further show the difference in adaptation between low stiffness and high stiffness fields (Fig. 5A). At lower stiffness levels, the area reaching deviation in catch trials was negative, indicating an adaptive mechanism that compensated for the field dynamics and resulted in straight-line movements in the presence of the field. At higher stiffness and curvature levels (Fig. 8A), area reaching deviation for after effects became positive, consistent with after effects in the direction of the applied forces and approximately following the profile of the virtual boundary. The magnitude of this positive after effect increased with increasing stiffness. Below a threshold value ($K \approx 1,200$ N/m; $\kappa = 15$ m⁻¹), the magnitude of the negative after effect increased with decreasing stiffness. In the case of high curvature interactions, subjects positive after effects persisted throughout the continuum of stiffness levels. While after ef-

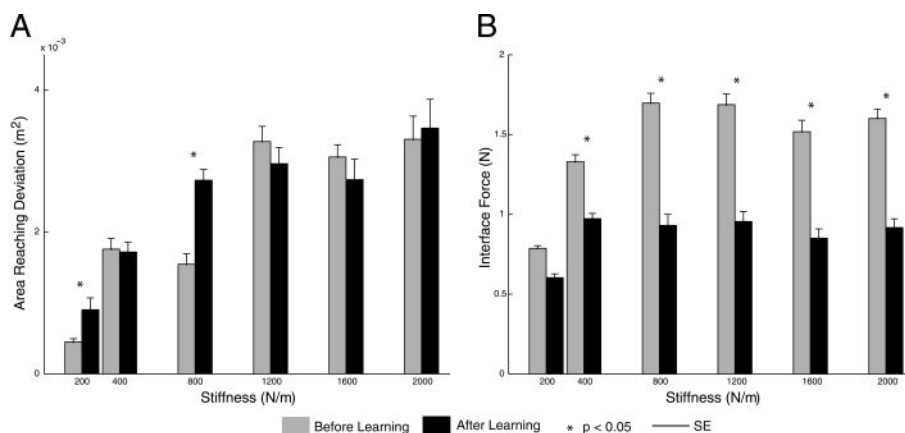


FIG. 9. Learning data for the high-curvature group. Measures shown are an average of the 1st and last 5 trials averaged across all subjects. A: ARD. B: interface force.

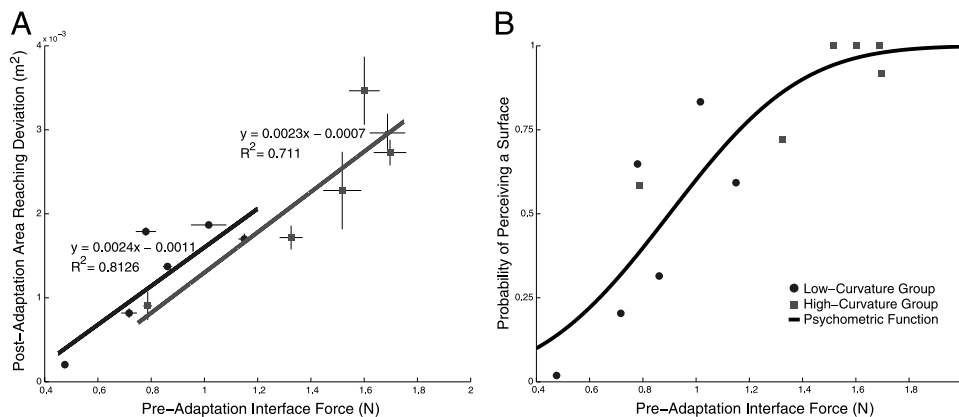


FIG. 10. Unified curvature results. A: ARD after learning vs. interface force before learning for both the low-curvature and high-curvature groups. B: unified psychometric function of perception of surfaces for an average interface force before learning.

fects were always positive during these interactions, the magnitude of the after effects increased as surface stiffness increased.

Taken together, these data suggest that subjects may have learned to respond to the perturbation in two ways: 1) by enforcing a nominal trajectory (the straight line from start to end target) at low stiffness and 2) by modifying the nominal trajectory, so as to comply with the perceived object boundary. The two responses are evident at the extremes of the tested stiffness values: the first response appears at low stiffness, whereas the second appears at high stiffness. Interestingly, however, we did not observe a sharp transition between these responses, but a smooth change from 1 to 2. We wish to stress that, in the context of force field adaptation, this is a rather paradoxical finding.

Based on earlier studies of adaptation, one would expect to observe increasingly larger after effects as the intensity of the perturbing field increases. In contrast, a smooth transition of responses, such as the one observed in this study (Fig. 5A), corresponds to a progressive reduction of the after effects as the force field stiffness increases. The tendency to larger after effect with increasing stiffness would have been consistent

with a discrete switching of responses when the field stiffness reaches a perceptual threshold. However, our results are unequivocally dismissing such a possibility. Instead, we find a gradual transition of after effects, from compensatory to compliant responses. This modification suggests that subjects alter their desired trajectory of movement in the face of environmental conditions. In the case of low stiffness, the desired trajectory is a straight line, whereas at higher stiffness, the desired trajectory is one that traces the object boundary. As surface stiffness increases, and interaction forces begin to increase, subjects may modify their desired trajectory of movement to accommodate the increasing forces of interaction. Rather than fighting the interactions forces through the continuum of surface stiffness, subjects develop a desired trajectory that maintains a constant level of interaction force and conforms to the object boundary.

The gradual transition of responses suggests that subjects may execute hand movements by combining multiple modules of control. This is consistent with the view that movements are generated by a combination of time-varying force fields (Bizzi et al. 1991, 1995; d'Avella and Bizzi 1998). The control module that dominates during interaction with low stiffness

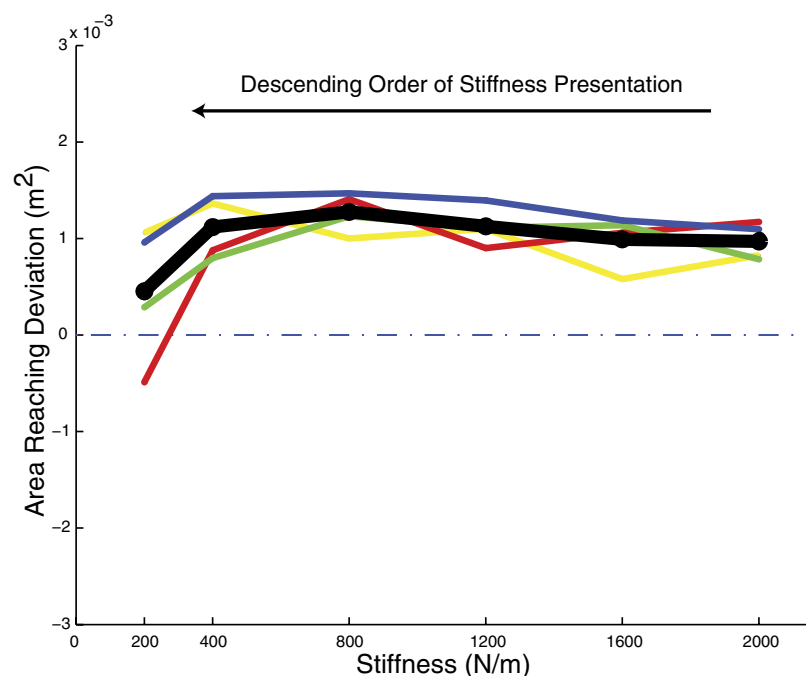


FIG. 11. ARD for catch trials of subjects interacting with a surface of curvature $15 m^{-1}$. Surfaces were presented in order of descending stiffness. Colored lines are data from single subjects; bold black line is the group average.

surfaces is one that strives to resist the perturbation of the field and recover a straight motion of the hand across the external field. At higher stiffness levels, the prevailing control module is one that modifies the nominal trajectory to comply with the object boundary. Through a continuum of force fields, the weighting of these two modules would result in the observed smooth transition of learned behavior.

While the concept of two control modules being combined to form field/object representations is plausible, this is not the only plausible explanation of subjects' behavior. Rather than a linear interpolation between two control schemes, subjects' adaptation may also be described by a simple continuous representation that estimates the external state as a function of experienced dynamics. This idea of a single continuous representation is supported by the linear relationship between pre-adaptation interface force and postadaptation after effects (Fig. 10A).

The invariance of average interface force after learning, together with the consistent relation between initial interface force and final adapted response, is in holding with other findings that suggest that there may be very simple mechanisms for scaling muscle activations and coordination patterns to produce consistently low amounts of net fingertip force (Valero-Cuevas 2000). Subjects may choose control policies that result in the nominal interface force they are willing to sustain. This level of interface force remains constant across stiffness levels within experiments with the same curvature. The idea of constancy of interaction force has also been reported in another recent haptic contact experiment, in which subjects explore a virtual environment of varying stiffness using an instrumented stylus (Walker and Hong 2004). It has also been shown that there may be very simple mechanisms for scaling muscle activations and coordination patterns to produce consistently low amounts of net force.

The idea that the nervous system uses an invariant average interface force as a cue for the mediation of control policies is further suggested by the similarity in behaviors seen for surfaces of different curvature. It is likely that with a surface of higher curvature, subjects experience larger interface forces caused by an initial increased level of surface penetration. This may explain why they tend to comply with the surface curvature starting from the lowest stiffness levels.

One should observe that the interface force is not, per se, a good classifier of the rigidity of a boundary. Different interface forces against a given object can be generated by hand movements driven by different motor commands. One can deliberately push against a constraint or generate a light touch. However, given an invariant motor command, boundaries with different degrees of rigidity will induce different levels of interface force. The variable pattern of contact forces in the initial phase of each experiment (Figs. 4B and 7B) indicates that subjects produced a relatively stereotyped motor command, based on the assumption that the hand was to move in free space. Under this condition, a given level of contact force can be taken as an indicator of the rigidity of the encountered boundary and can therefore be used for classification (Fig. 10B).

A physiological account for the detection and regulation of interface force may result from the manner in which tactile afferents respond to touch. During grip tasks, FA I mechanoreceptors in glabrous skin tend to initiate a response and fire at

lower force contact and be suppressed and turn off once a threshold of force has been reached (Johansson and Westling 1991). Collectively, a network of receptors distributed on the surface of the hand allow for a narrow range of detection of force (pressure) and its geometric distribution on the hand. During a high level of contact force, a large number of receptors in the network may be overly excited and become inactive, resulting in a deficit in sensory information. Conversely, if too low a level of force is applied a smaller number of receptors may be activated, again resulting in a deficit in sensory information. Therefore there may be an optimal contact force that allows the task to be completed while maximizing activation of the receptor network and thus maximizing sensory and haptic feedback about the surface in contact.

While the two adaptive behaviors are present (i.e., restoration of an unperturbed motion and a compliant response), there seems to be a rather gradual transition between them. This finding is in contrast with our own initial prediction and with some known perceptual transitions (e.g., the Necker cube illusion). Furthermore, we found that the observed response across a variety of stiffness values leads to a constant average interaction force after adaptation. This gives support to the hypothesis that the adaptation response may be mediated by a mechanism that attempts to enforce a constant interaction force (rather than a nominal trajectory). However, further research is needed to understand the control mechanisms the CNS uses when developing internal representations of the objects with which we interact.

GRANTS

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