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Enhanced Visual Error in a Coordinated Pinch Task

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***Abstract*— Our previous work has shown that visual distortion of subject-controlled goals can be used to manipulate force production and movement distance. Thus, visual distortion may be a helpful addition to robotic rehabilitation for brain-injured and stroke patients. In this work, we investigated the effects of distortion on unimpaired subjects learning a two-finger coordinated pinch task. Rather than distorting the subject's goal, we enhanced the apparent error attributable to one or both fingers. Distortion affected the distribution of attention between the two fingers; when the error enhancement was given to one finger, the performance of that finger improved relative to the other. This result indicates that enhanced visual error could be used to manipulate the performance and the coordination pattern between fingers to achieve desired movements during rehabilitation.**

I. Introduction

THE growing field of rehabilitation robotics has expanded the range of rehabilitation options available to individuals disabled by disease or injury. However, rehabilitation robotics also has the potential to address perceptual variables that can influence therapy, and this possibility has not yet been widely explored. When working with a therapeutic robot, a patient often receives information about his or her performance via a computer screen. This visual feedback has been used to make rehabilitation more entertaining [1], but it can also be controlled to influence the patient's perception of the therapy.

The goal of our research is to improve patient performance during therapy using visual feedback manipulation. In particular, we are investigating the effects of visual distortion. Patients may resist striving for difficult goals in therapy due to entrenched habits [2], increased perception of task difficulty [3], or personality variables such as low self-efficacy or a fear of failure [3, 4]. We believe that visual distortion can be used to help patients overcome a reluctance to move beyond an established level of performance. We plan to use visual feedback to establish a metric of performance for a given rehabilitation task and then distort this metric such that improved performance is required to cause the same visual response. To test this hypothesis, we are focusing on rehabilitation of the hand and fingers.

In previous experiments, we showed that visual distortion can be used to manipulate force production [5]. Each subject attempted to remain consistent while repeatedly producing a numerically specified level of force with the index finger. The subject saw a visual display corresponding to the force produced, and we implemented visual distortion by gradually changing the visual feedback so that a particular force magnitude appeared progressively smaller. We were able to use this visual distortion to increase the force produced by young and elderly unimpaired subjects and by a traumatic brain injury patient. Visual dominance also occurred for movement distance and when subjects were informed of the possibility of distortion.

In our previous work, subjects were free to set the target force or distance specified by a particular numerical magnitude. The purpose of the distortion was to change the force or distance goal corresponding to each level. The present work used a different distortion paradigm that we call "error enhancement." According to this paradigm, subjects were asked to work at a demanding task with an objective performance criterion. Departures from ideal performance were displayed as errors, which were distorted to appear larger. A coordinated pinch task was chosen because coordination of multiple fingers is important for many activities of daily living. As a subject learned the coordination task, we presented feedback about his or her error in performance. Distortion was implemented as an artificial inflation of this error. We first investigated whether error enhancement would improve performance. Some evidence to this effect for one limb comes from Patton et al. [6], who showed that magnifying visual error by physically displacing the arm's trajectory resulted in smoother and straighter trajectories in stroke patients. We further asked whether distortion of the feedback corresponding to a single finger would allow the experimenters to manipulate the coordination pattern between two fingers. This might occur, in particular, if the feedback induced subjects to focus their attention on the distorted finger. Alternatively, it is possible that trying to improve just one finger at a time provides a superior training method relative to attempting to coordinate both, in which case transfer between the fingers could be observed.

II. Methods

Sixty-one subjects between 18 and 35 years of age participated in this experiment. No subject had a history of known neurological injury. All gave informed consent and performed the experiment with the dominant right hand.

The robotic environment used in this experiment is shown

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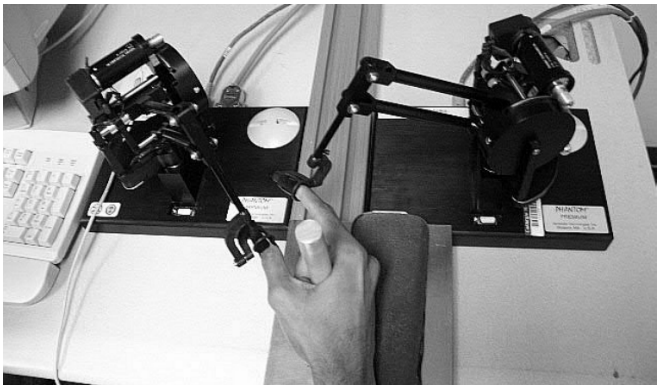

Fig. 1. The experimental environment. The subject placed the thumb in a finger cuff attached to the left robot; the index finger was placed in a finger cuff attached to the right robot. The robots were used to simulate a virtual object between the index finger and thumb.

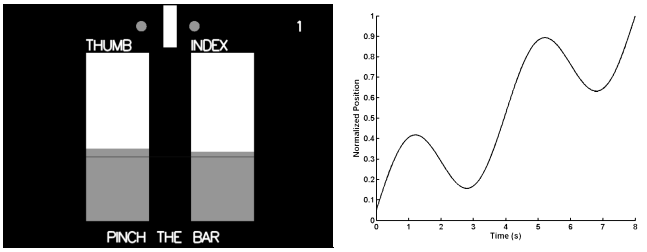

Fig. 2. Left: The visual feedback seen by the subject during a trial of the experiment. The line crossing both bars moved the same way on each trial, and subjects tried to move the index finger and thumb in such a way that the tops of the shaded rectangles tracked the line. Right: The normalized position of the target line as a function of time. When the normalized position is equal to 0, the target line is at the bottom of the visual feedback bars; when the normalized position is 1, the target line is at the top of the feedback bars.

in Fig. 1. Two Premium 1.0 PHANTOM™ force-feedback robots (SensAble Technologies, Inc.) were used. Each robot had 3 active degrees of freedom and a position resolution of 0.03 mm [7]. To each robot was attached a standard finger cuff made by Sensable Technologies, Inc. The subject placed the index finger in one finger cuff and the thumb in the other. The remaining fingers grasped a post to keep the hand stationary throughout the experiment. The subject sat with the arm flexed at the elbow and the forearm horizontal.

During this experiment, each subject learned to move the index finger and the thumb in a particular target pattern while receiving visual feedback corresponding to each finger. On each trial, the subject started with the index finger and thumb extended. The visual feedback seen by the subject during each trial is shown in Fig. 2 left. The small white rectangle at the top of the screen represented a virtual object implemented using the force-feedback capabilities of the robots. The circles to the left and right of the white rectangle represented the thumb and the index finger, respectively. The large bar on the left represented the distance from the starting position of the thumb to the edge of the virtual object. The bar on the right represented the same for the index finger. The shaded portion of each bar represented the normalized position of the corresponding finger between the starting position and the virtual object (0 at the bottom of the bar and 1 at the top).

The line crossing both bars showed the subject the target movement pattern for the thumb and the index finger. The line started at the bottom of the bars, and as soon as the subject crossed the line with the shaded portion of either bar, the line began to move. On every trial, the line moved for 8 seconds according to the equation $L = 0.5 + 0.95\frac{\Delta t}{8} + 0.2375\sin\left(\frac{4\pi\Delta t}{8}\right)$, where Δt is the time in seconds that has passed since the beginning of the trial and L is the normalized position of the line along the bars (Fig. 2 right). The subject's goal was to learn to keep the tops of the shaded portions of the bars as close to the line as possible. For each trial, we computed the mean absolute difference between the normalized position of each finger and the target line; we call this the trial absolute error for each finger. The trial absolute error for each finger was displayed to the subject after each trial. As an incentive to maintain subject attention to the task, each subject was told that he or she would receive a candy bar if the error over the entire experiment was below a predetermined threshold. The subject was not told the threshold.

Visual distortion was implemented as a magnification of the error between the thumb and/or index finger position and the position of the target line. When the visual feedback of the index finger was distorted, the signed error between the index finger and the target line was computed in real time and then increased by 20%. The height of the shaded bar on the screen at each time point was obtained by adding the modified error to the height of the target line. Thus, the height of the shaded bar no longer corresponded faithfully to the position of the subject's index finger. The numerical error for the index finger given to the subject at the each of each trial was also increased by 20%. The feedback for the thumb was distorted in the same way. We measured the effect of the different distortion modes on learning as measured by the trial absolute error.

Three experimental conditions were considered in addition to a control condition in which the visual feedback was not distorted. Ten subjects participated in each condition, except for the ITB (index-thumb-both) condition, which had eleven subjects. No subject participated in more than one condition. In the ITB (index-thumb-both) condition, each subject experienced 80 training trials in which there was no distortion. The subject then encountered a block of 40 trials in which the visual feedback for the index finger was distorted, followed by a block of 40 trials in which the visual feedback for the thumb was distorted. The experiment concluded with a block of 40 trials in which the visual feedback for both the index finger and the thumb was distorted (scale change relative to original feedback). The TIB (thumb-index-both) condition was similar, except that the block of trials with distorted thumb feedback occurred before the block of trials with distorted index finger

feedback. In the B (both) condition, the initial learning period of 80 trials was followed by a single block of 40 trials in which the visual feedback for both the index finger and the thumb was distorted. Breaks were given frequently to prevent subject fatigue. Post-experiment questionnaires revealed that subjects did not detect the distortion. All but four subjects stated that they tried to move the finger and the thumb in a coordinated way.

After the first 20 trials, one random trial out of every 20 was a no-feedback trial. On the no-feedback trials, the normalized position of each finger was not shown; the screen appeared the same, except that no part of the visual feedback bars was shaded. These trials were included to assess whether subjects could reproduce the target movement without feedback about finger position.

In these experiments, the subject's attention was divided between the index finger and the thumb. To examine how this affected our results, we also ran a control experiment in which each subject tried to learn a target pattern using only the thumb. This experiment was similar to that described above. Only one robot was used, and the subject only saw feedback corresponding to the thumb. The target pattern of movement shown by the line was the same. Two conditions were considered in this experiment. One group of ten subjects experienced 80 trials with no distortion, then 40 trials with 20% distortion, followed by another 40 trials with no distortion. Another group of ten subjects experienced 120 trials with no distortion, followed by 40 trials with 20% distortion.

III. Results

A. Learning of the Target Task

Data from the control subjects who used both the index finger and the thumb were examined to determine whether learning occurred for the target task. The trial absolute error (the mean absolute difference between the normalized index finger position and the position of the target line) for the index finger was added to that of the thumb for each trial. This sum was averaged over trials 21-40 and over subjects to obtain the mean total absolute error for these trials, which was compared to the mean total absolute error for trials 181-200 using a t-test. Data from no-feedback trials were excluded from this analysis. The first twenty trials were not used for this comparison because some subjects misunderstood the task during the first few trials. The mean total absolute error for trials 21-40 was significantly different from that for trials 181-200 ($p < 0.001$). The learning trend in the control data can also be seen in Fig. 3. When the mean total absolute error for the index finger was compared to that of the thumb, the thumb error was significantly larger for trials 21-40 ($p = 0.0068$), but not for trials 181-200 ($p = 0.128$).

To investigate the reasons for these decreases in error, we compared the mean absolute difference (computed over trials and over subjects) between the normalized position of the index finger and the normalized position of the thumb during trials 21-40 and trials 181-200. The difference in position was less for the later trials ($p < 0.001$), which means that subjects learned to move the thumb and the index finger in a more coordinated fashion during the experiment. We also considered the lag between the position profile of each finger and the position of the target line. The lag for each trial and finger was computed by finding the difference in time that maximized the correlation between the finger position and target line position. Essentially, this indicates the time period by which the subject's response trailed the target movement. The mean lag (computed over trials and over subjects) for trials 21-40 was not significantly different from the lag for

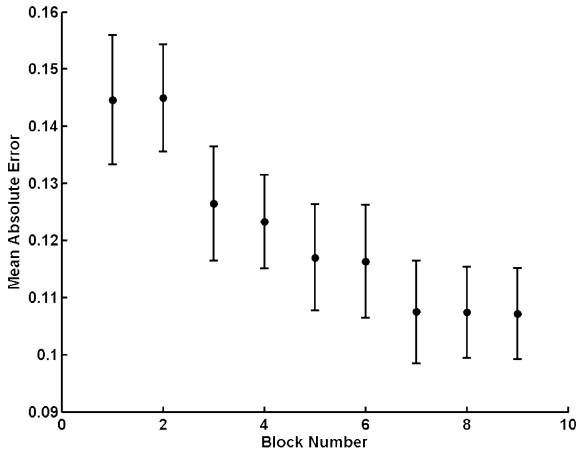

Fig. 3. Learning over time. Data from the control subjects were divided into blocks of twenty trials. Block 1 corresponds to trials 21-40, block 2 to trials 41-60, etc. A decrease in the total mean absolute error as a function of block number occurred as the experiment progressed.

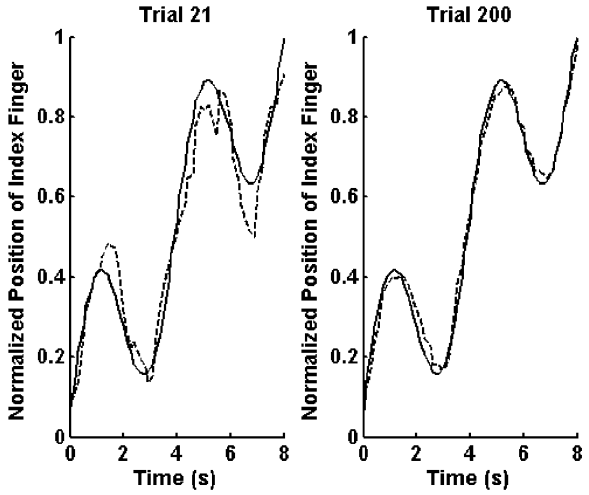

Fig. 4. Left: Performance of a single subject on trial 21. The solid line represents the normalized position of the target line as a function of time, and the dashed line represents the normalized position of the index finger. Right: Performance of the same subject on trial 200. The subject has reduced the error of the index finger relative to the target line, but the lag between the target line and the path of the index finger has remained approximately the same.

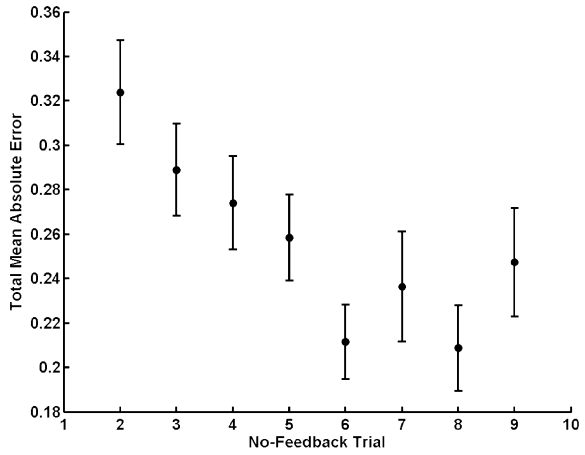

Fig. 5. Results of the no-feedback trials for control subjects. Data from the first no-feedback trial were excluded because many subjects misunderstood the task (see text). The total mean absolute error was significantly larger for no-feedback trials than for the with-feedback trials, but a decrease in total absolute error and an increase in coordination did occur during the experiment for the no-feedback trials.

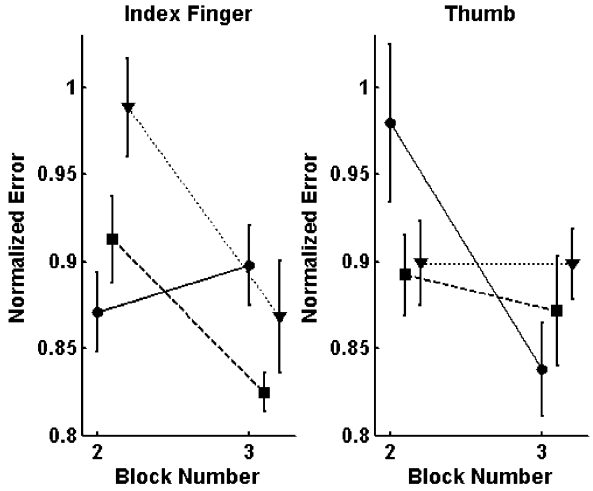

Fig. 6. The effects of distortion on learning of the coordination task. Squares represent control subjects, circles represent subjects in the ITB condition, and triangles represent subjects in the TIB condition. Left: The normalized error for the index finger. The change from block 2 to block 3 for the ITB condition is significantly different from that of the controls. Right: The normalized error for the thumb. Again, the change from block 2 to block 3 for controls was significantly different from that for subjects in the ITB condition. No differences were found between control and TIB subjects.

trials 181-200 for either the index finger or the thumb (p = 0.775 for index, 0.501 for thumb). Subjects learned to keep the normalized position of each finger closer to the target line during the experiment, but the mean lag of each finger remained the same (Fig. 4).

Data from the control subjects were also used to examine whether learning in the with-feedback trials transferred to improvements in performance on the no-feedback trials (Fig. 5). Subjects had much larger errors on the no-feedback trials throughout the experiment. Even at the end of the experiment (trials 181-200), the mean total absolute for the no-feedback trial was significantly different larger than that for the with-feedback trials ($p < 0.001$). However, the difference between the mean total absolute error on the second and last no-feedback trials was close to significance (p = 0.0542), indicating a trend toward a learning effect in overall error. The first no-feedback trial was excluded because despite instructions, many subjects were confused when the first no-feedback trial occurred. The mean absolute difference between the normalized position of the index finger and that of the thumb decreased from the second no-feedback trial to the last (p = 0.0240), showing an improvement in coordination of the finger and thumb on the no-feedback trials.

B. Effects of Distortion

To assess the effects of the distortion conditions, the data for each ITB, TIB, and control subject were divided into four blocks: trials 41-80, trials 81-120, trials 121-160 and trials 161-180. The first forty trials were regarded as practice and excluded, because we wanted to examine how distortion affected performance after subjects had acquired a level of mastery of the task. For each subject, the trial absolute error for each finger was averaged over each block. Next, for each finger and each subject, the mean absolute errors of blocks 1-4 were divided by the mean absolute error for block 1 to reduce variability due to individual differences in baseline error. We used this error measure, which we will call the normalized error, for our analysis. The normalized error measured performance improvement for each subject as a proportion of the baseline error. The data for subjects in condition B were analyzed similarly using only two blocks, trials 41-80 and trials 81-120.

To determine whether distortion affected terminal performance, we compared the mean normalized error in block 4 for each distortion condition to the control. None of these comparisons was significant (ITB: p = 0.0669 for index, 0.689 for thumb; TIB: p = 0.144 for index finger, 0.991 for thumb). Similarly, the mean normalized error for block 2 of condition B was compared to mean data from block 2 for the control condition; there was no significant difference for either finger (p = 0.704 for index finger, 0.835 for thumb).

Though distortion did not affect subjects' final performance in the task, it did appear to change the shape of the learning curve, as seen in Fig. 6. To investigate the significance of these apparent changes, we conducted two types of comparisons. First, we compared experimental and control subjects using the normalized error for each finger in blocks 2 and 3, in which distortion of a single finger was imposed (the finger being distorted changed between blocks). A difference would indicate an effect of distortion. The normalized index finger error for ITB subjects in block 2 did not differ significantly from that of control subjects (p = 0.235), but the ITB index error in block 3 was significantly larger than the control error (p = 0.0128). The normalized thumb error for ITB subjects did not differ from the control

error in either block, though the comparison for block 2 approached significance (p = 0.113 for block 2, 0.425 for block 3). No significant differences were found between TIB and control subjects.

The second comparison we made between groups was with respect to the change in normalized error when we changed the finger being distorted (between blocks 2 and 3). A significant difference in this measure would indicate an effect of distortion different from the learning effect seen in the controls. For the index finger of ITB subjects, the difference between the mean block 2 error and the mean block 3 error was significantly smaller than for control subjects (p = 0.0034). For the thumb, the error difference was significantly larger for ITB subjects than for controls (p = 0.0046). These results tell us that the learning curve for each finger changed differently from block 2 to block 3 for ITB subjects when compared to control subjects. Specifically, distortion did not make the distorted finger perform better, but it did negatively affect the performance of the non-distorted finger. Corresponding changes were not observed for TIB subjects.

C. Control Experiment Using Only the Thumb

Data from each subject in the thumb-only control experiment were divided into three blocks (trials 41-80, trials 81-120 and trials 121-160) and analyzed as above. No significant differences were observed between the group that received distortion in block 2 and the group that received distortion in block 3.

IV. Discussion

A. Learning of the Target Task

We examined learning in a challenging coordinated pinch task. We found that the average time by which the subject trailed the target movement remained constant while subjects learned to reduce their mean absolute error. Increased coordination of the index finger and thumb in normalized distance space was a product of this task, as subjects had to track the target line with both fingers simultaneously. Subjects stated that they performed the task by concentrating on moving the index finger and the thumb together, though they had to move the two fingers at different rates because the index finger and the thumb did not necessarily start at the same distance from the virtual object.

The results of this experiment show that subjects can learn to control even performance variables that are not clearly related to daily tasks. While humans do have to consider the position of the index finger and thumb in daily life, subjects in this experiment were required to move the thumb more than they naturally tended to do when grasping objects, and they had to track a target with an arbitrary sinusoidal path. Latash et al. [8] found that subjects could not learn to overcome certain patterns of coordination among the fingers. The results of this experiment show that the typical pattern of coordination between the index finger and the thumb can be modified through learning.

Learning in this coordination task transferred partially to the no-feedback case. In this task, subjects learned a particular pattern of movement as they tried to minimize visual error. Because emphasis was placed on the visual error, it is no surprise that a subject's error was greater when executing the learned movement without visual feedback of position. However, the mean total absolute error in the no-feedback case did seem to decrease as the experiment progressed, and subjects learned to move the index finger and the thumb in a more coordinated manner on the no-feedback trials. More transfer to the no-feedback case might have been observed if more no-feedback trials had been included. For effective learning and transfer of a motor task to occur, subjects must learn to use internal cues rather than relying on extrinsic feedback [9, 10].

B. Effects on Terminal Performance

One of our hypotheses for this experiment was that visual enhancement of error would improve the terminal performance. The improvement might be specific to the distorted finger, or decomposing the task might have a more generally beneficial effect across the fingers. It is also important to note that in an impaired patient, this approach might be used to focus selectively on more affected digits.

Although distortion affected ongoing performance while individual finger error was distorted, it did not improve terminal performance when both finger errors distorted together at the end of the experiment. In the experiment involving both fingers, there was no difference between the performance of control subjects and that of experimental subjects receiving distorted visual feedback for both fingers (B condition and the last block of ITB and TIB). Also, in the thumb-only experiment, distortion had no effect on the normalized error of subjects. These results are similar to those of [11], which reported that error augmentation using a multiplicative gain did not improve terminal performance in a reaching task. Error augmentation through a constant offset was found to be more effective [11], but that type of distortion would not be relevant for the task we considered.

The results of this experiment appear to contrast with those of our previous work, in which goal distortion was used to increase force production and movement distance over the time-course of a single session [5]. In general, our previous experiments asked subjects to produce a specified force or distance using one finger within their voluntary maximum. Subjects in this experiment, on the other hand, were learning a coordination task between two fingers, which is fundamentally more complex. It is understandable that more practice could be required in order to find persistent effects under these circumstances. Further work is needed to explore the parameters of this paradigm for effective longer-term learning.

C. Attentional Effects of Distortion

We believe that the primary effect of distortion in this experiment was to shift attention between the index finger and the thumb, with a corresponding decrement in performance resulting for the unattended digit. This is particularly clear for the ITB. When the index finger error was distorted (block 2), the thumb error tended to be higher than that of controls because subjects concentrated attention on the index finger. When distortion shifted from the index finger to the thumb (block 2 to block 3), ITB subjects showed an increase in the index finger error (countering the general learning trend) and a steep decrease in thumb error, in contrast to the trends for the control and TIB group. In block 4, the error for both fingers was distorted for ITB subjects, and they divided their attention between the two fingers in much the same way as control subjects.

Although the TIB group more closely mimicked the controls, they too showed a steep decline in index error and counter-learning trend in thumb error when distortion shifted from the thumb to the index finger (block 2 to block 3). The lack of significant differences between TIB and control subjects can be explained by the fact that the trial absolute error for the thumb was significantly larger than that of the index finger for control subjects at the beginning of the experiment. Both control and TIB subjects saw the thumb error as larger in block 2, and both groups focused attention on minimizing that error. The thumb error was not significantly different from the index finger error for control subjects at the end of the experiment. Thus, as the experiment proceeded, control subjects may have divided the attention more evenly between the index finger and the thumb, which may parallel the shift in attention of TIB subjects to the index finger error and then to both fingers.

D. Implications for Patient Work

This experiment has several implications for our planned work with patients. First, we learned that it is possible to change the coordination pattern between two fingers for unimpaired subjects and we hope to do the same for patients with abnormal coordination skills. Though the specific task used here may not be task-oriented enough for rehabilitation, we plan to use a similar task to train patients to bring the index finger and thumb together in a coordinated way for pincer grasp. Also, this work demonstrates that we should provide opportunities for patients to practice the target task without visual feedback to prevent dependence on the visual display. Finally, it should be noted that for patients whose coordination difficulties reflect a selective decrement in a particular digit, the present paradigm could guide their attention to that locus and hence could direct rehabilitative action to the point of greatest need.

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