On Learning to Move Randomly

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ABSTRACT. In 2 experiments, the authors examined whether and to what degree young adults can learn to produce random planar motion of the index finger or fingers. Three different types of information feedback were provided to the participants (N = 8 in each experiment) over up to 5 days of practice across the 2 experiments. The results from both experiments revealed that the participants produced a relatively low level of movement randomness in finger motion and that they did not learn through practice to enhance the stochastic properties of their movement under any feedback conditions. The findings provide further evidence that there are relatively tight constraints on the number of dimensions that are regulating single-limb planar motion and that those constraints are not susceptible to change through typical learning protocols.

Key words: constraints, degrees of freedom, learning, random movement

A learner’s goal in a task in motor learning is usually to produce an output that matches some internally or externally defined criterion that previously has not been consistently achieved. The criterion involves an outcome specified in either or both the spatial and temporal dimensions of task space and possibly a movement pattern that satisfies some particular set of spatial–temporal properties. In either case, the learner is trying to satisfy a particular constraint or invariant while producing some minimal level of variability on the task-relevant dimensions over successive trials. Natural observation and 100 years of motor learning research have shown that people are adept at learning a range of movement tasks (Mazur & Hastie, 1978; A. Newell & Rosenbloom, 1981; Thurstone, 1919; Woodworth & Schlosberg, 1938).

In theories of motor control and learning, the role that invariants play in the organization of movement has often been emphasized (e.g., Bernstein, 1967; Kelso, 1995; Kugler & Turvey, 1987; Schmidt, 1975; Turvey, 1990). Indeed, currently there is much research activity that attempts to capture the organization of movement in terms of a low-dimensional relation. The variance of movement outcome has become more important in motor control research (cf. Newell & Corcos, 1993; Newell & Silfkin, 1998), but movement invariance is still considered to be more central to theorizing than the variance. Generally, the invariance of movement is considered more central because it is viewed as a window into the deterministic organization of the system output, whereas the variance is interpreted as a reflection of noise.

Here, we reversed that strategy in an operational sense by invoking as our goal in the experimental task the production of a random set of movement properties in the planar motion output of a single limb. In other words, our experimental task goal was to produce an outcome that matched the spatial and temporal properties of white Gaussian noise (Pierce, 1961). It is well established that people have difficulty producing random strings of symbols (Rosenberg, Weber, Crocq, Duval, & Macher, 1990; Wagenaar, 1972), but a random task constraint has not been examined directly in the movement domain.

In earlier experiments, subjects have been found to have a great deal of difficulty attempting to meet the task constraint of moving randomly, in that there were limited dimensions to the dynamical planar motion of the finger, hand, and lower and upper arms (Newell, Challis, & Morrison, in press). The results of those studies revealed that the structural and functional constraints upon planar motion at a single joint coalesce to provide a set of relatively low-dimensional boundary conditions. The implication is that

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the control structure induces a more limited reduction in the
dimensionality of the system's degrees of freedom than is
typically postulated in theories of movement control (Bernstein,
1967; Saltzman, 1979; Turvey, Shaw, & Mace, 1978).

The practice and information feedback provided to the
participants in the experiments of Newell et al. (1999) were,
however, very limited. It is well established that information
feedback can be a very powerful learning variable and that
the appropriate type of feedback for learning is, to some
degree, task dependent (Newell, 1991; Newell, Morris, &
Scully, 1985; Swinnen, 1996). That consideration leaves
open the possibility that with a more direct form of informa-
tion feedback about the randomness of the just-comple-
ted movement segment participants could learn with practice
to enhance the stochastic properties of movement output,
particularly if they are given a longer practice duration.

In this study, then, we examined whether and to what
degree participants could learn to enhance the random prop-
erties of their movement output through practice and differ-
ettional types of information feedback. In Experiment 1,
one group of participants was given 5 days of practice with ter-
minal information feedback and was contrasted against a
group that was given no augmented information. In Exper-
niment 2, there were two conditions of concurrent informa-
tion feedback that involved the presentation in real time of
the kinematics of either the last 10 s of the ongoing trial or
the complete trial to date over 3 days of practice. It has been
shown that memory demands influence the production of
random symbol sequences (Rosenberg et al., 1990), and we
wanted to contrast the influence of very recent movement
information versus complete trial-to-date information as
feedback. We anticipated that the findings from these ex-
periments would provide further evidence about the level and
existence of the structural and functional constraints on
planar motion at a single joint.

EXPERIMENT 1

In Experiment 1, participants in two independent condi-
tions learned to move the index finger or fingers randomly
over 5 days of practice. In one condition, the participants
received no augmented information about their perfor-
mance on the task. In another condition, the participants
received on the completion of each trial a computer-gener-
atived graph of a 10-s segment of the position–time profile
from the middle of the first, middle, and last 30 s of the just-
completed trial. The participants also performed a series of
preferred-frequency trials to provide a comparison with the
random movement condition (Kugler & Turvey, 1987).

Method

Participants

The participants were 8 right-handed adults (5 men, 3
women; mean age = 30.75 years), who were students at The
Pennsylvania State University. All participants provided in-
formed consent before testing. The experimental procedures
used in this study were approved by the Office of Regu-
latory Compliance at The Pennsylvania State University.

Apparatus and Procedures

The participant sat on a chair at a table of normal height.
The forearms and hands were placed on the table, providing
a base of support for the oscillatory movements (flexion–extension) of the index finger or fingers in the hor-
izontal plane. The hands were situated on the table so that
they were a comfortable distance from the torso, and the tips
of the index fingers were about 2.5 cm apart. A flexible
goniometer (Penny & Giles Biometrics Ltd., Cwmfelinfach,
Gwent, UK), which was attached to the dorsal aspect of the
fingers, provided a measure of the excursion. The proximal
end of the goniometer was fixed midway down the shaft of
the second metacarpal, and the distal end was attached to the
middle phalanx of the index finger. That positioning meant
that the goniometer measured the change in angle of the sec-
ond metacarpophalangeal joint of the index finger. Par-
cipants were asked to limit movement to that joint and to
ensure no motion about the interphalangeal joints.

The joint angle data were sampled at 100 Hz and collect-
ed on a 486 IBM-compatible computer through a 12-bit
analogue-to-digital converter. The data were run through a
30-Hz low-pass filter because that cut-off includes the
known frequency properties of the fastest intentional finger
motion and the properties of physiological tremor (Elble &
Koller, 1990). With a custom-designed analysis program,
we determined the peaks and troughs of position in the time
series and the time to reach each of those landmarks. To
eliminate small changes in direction that might be caused
by environmental noise, the program required that a change
in direction of at least 2° follow the peak or trough that had
been identified. We estimated the power spectral density of
the position–time signal by using Welch's averaged peri-

Participants practiced the random movements on 5 con-
secutive days. The practice on each day consisted of five tri-
als of random motions with the right finger alone and five tri-
als with both fingers together. The learning trials were 2 min
in duration with 1-min rest intervals between each trial. The
order of the conditions (right finger alone or both fingers
together) was counterbalanced across participants and days.
Participants were instructed to move the finger or fingers in
a random fashion. Specifically, participants were instructed
to produce as many different combinations of speed and
range of motion as they could so that the movement seg-
ments would be produced in a random order. The instruc-
tions elaborated the full meaning of that statement, and the
learning trials did not begin until the experimenter was
assured that the participant fully understood the instructions.
All learning trials were performed with eyes closed because
it was previously found (Newell et al., 1999) that participants
produce movements slightly although not significantly more
randomly with eyes closed than with eyes open. The instruc-
tions were repeated on all subsequent testing days.

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315

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During the rest periods between each test trial for the no-feedback group, the task instructions were repeated, and participants were encouraged to produce movements during the next trial that had a higher level of randomness. Participants were also encouraged on Days 2–5 to produce movements with a higher level of randomness than those they had produced on the previous day. During the rest periods for the feedback group, the participants were given the same general instructions about random motion, and they also viewed a computer screen that provided a view of their movements during a 10-s segment of the first, middle, and last 30-s segments of the trial. The position–time data of those three segments of the trial were shown on a computer screen so that the participant could assess the degree of randomness of the movement output.

On the 1st, 3rd, and 5th days, participants performed preferred trials prior to the learning trials. Two preferred trials were performed with the right finger alone, and a further two trials with both fingers together. The participants were asked to oscillate their finger or fingers by using a speed and range of motion that they thought would allow them to produce oscillations comfortably with a low level of variability for a 2-min trial. Participant’s eyes were closed for the duration of each 2-min preferred trial. One-minute rest periods were provided between each preferred trial. Augmented information feedback for the preferred condition was provided as outlined for the random conditions. Preferred oscillatory limb motions have been shown to be produced with low variability and to appear stable from day to day (Kugler & Turvey, 1987).

On the 1st day of testing, prior to the preferred and learning trials, participants performed several 10-s trials so that we could determine the range of motion and fastest and slowest speeds they were capable of producing. Those trials were performed with the eyes open. Participants performed one range of motion trial. For that trial, participants were asked to move both fingers together as far as possible in the flexion and extension directions at a comfortable speed. The fast and slow movement trials were each performed with both fingers together and with the right hand alone. For the fast movement trials, participants were asked to oscillate their finger or fingers as fast as possible, using a range of motion of their choice. Instructions for the slow movement trials were to move the finger or fingers as slowly as possible, regardless of the distance the fingers traveled.

**Results**

The results for the preferred and random movement conditions are split into two main sections that relate to (a) the distributional properties of the movement space–time characteristics and (b) the irregularity of the sequential properties of the time series. We analyzed each of the preferred movement dependent variables via a 2 (feedback) × 3 (day) × 3 (finger condition) analysis of variance (ANOVA) with repeated measures on the last two factors. The random movements had the same design, except that there were 5 days in the ANOVA.

**Preferred Movements**

*Space–Time Characteristics*

With respect to movement space-time characteristics, in Figure 1 is shown a 10-s segment of the position–time data for an exemplary trial from both a preferred and a random movement trial condition. As expected given the different task demands, the preferred condition showed less variability in the space–time characteristics of the finger motion than the random condition.

We examined the amplitude of motion by calculating the amplitude from each peak to the succeeding trough and from each trough to the succeeding peak in the time series. The group, F(1, 6) = 0.52, p > .05, day, F(2, 48) = 0.43, p > .05, and finger condition, F(2, 48) = 2.83, p > .05, main effects for mean amplitude were not significant. The main effect almost reached the traditional .05 significance level; the near-significant result was generated by the right finger’s larger mean amplitude in the single-limb condition (M = 32.95°) than in the dual-finger condition (M = 28.21°), whereas the mean amplitude of the left finger motion in the dual-limb condition was 30.60°. The Group × Day effect, F(2, 48) = 2.82, p > .05, almost reached significance. In the no-feedback condition, the mean amplitude of motion was reduced over the 3 practice days, whereas in the feedback condition, the amplitude of motion was increased. Essen-

![FIGURE 1. Exemplar 10-s segments of the position–time trial data from the preferred and random motion of single-finger oscillation conditions: (top) random condition; (bottom) preferred condition.](image-url)
tially the same pattern of findings emerged for the analysis of the variability of the amplitudes (standard deviation).

The time between the peaks (period) was calculated and subjected to the same analysis procedures that were used for the amplitudes. There were no main effects or interactions for the mean or standard deviation of the period (ps > .05).

Power spectrum analysis was performed as another test of the period or frequency properties of the different oscillatory movements. The dependent variables measured were the modal frequency (the point that carried the most power in the spectrum) and the amplitude (power) at that modal frequency. There were no main effects for feedback or day on the modal frequency of the preferred movements (ps > .05). There was, however, a Feedback × Day interaction, $F(2, 48) = 10.15, p < .01$, with the modal frequency increasing over days for the no-feedback group but decreasing for the feedback group. The overall mean frequency of the preferred movements was 1.75 Hz. Generally, for each trial the spectrum was very peaked at the preferred frequency and the range of frequencies that showed power (above 5% of the peak) was between 0 and 6.54 Hz. The effects for power at modal frequency followed the frequency data with a complementary trend in the Feedback × Day interaction, $F(2, 48) = 7.71, p < .01$.

Regularity of Movement

We assessed the regularity of the movement output through the index of approximate entropy (ApEn; Pincus, 1991, 1994). ApEn produces a measure of the degree of regularity or irregularity of a time series through conditional probability procedures. Signals that are more random in nature produce a higher ApEn value (tending toward an upper limit of 2), with lower scores (tending toward a lower limit of zero) reflecting signals that display higher regularity in the time series. In the ApEn analysis, we used a standard run length of $m = 2$ and filter width of $r = .25$ (Pincus, 1991).

In Figure 2, the mean ApEn values for the preferred conditions are shown as a function of feedback and finger conditions over days. The analysis showed that there was no main effect for feedback condition, $F(1, 6) = 0.24, p > .05$, or days of practice, $F(2, 48) = 1.82, p > .05$. There was an interaction between feedback condition and day, $F(2, 48) = 7.50, p < .01$, and between feedback condition and finger, $F(2, 48) = 3.82, p < .05$. Post hoc analysis revealed that the feedback group was significantly higher on Day 1 than the no-feedback group, but that effect was not present on Days 3 and 5. Post hoc analysis also showed that feedback elevated the irregularity in the right-finger-alone condition but not in any other finger condition.

Random Movements

Movement Space–Time Characteristics

The analysis of the mean amplitudes of motion showed that there was an effect for the finger condition, $F(2, 84) = 32.58, p < .01$, and for the Group × Day interaction, $F(4, 84) = 2.59, p < .01$. Post hoc analysis revealed that the left finger in the dual-limb condition (M = 29.68°) had a significantly larger mean amplitude than the right finger in the single-limb (M = 22.95°) and the right finger in the dual-limb (M = 22.45°) conditions. There was a significant and persistent decrease in the amplitude of motion of the no-feedback condition over the 7 days of practice, whereas that change in amplitude was not apparent in the feedback condition. All other main and interaction effects were non-significant (ps > .05).

The analysis of the mean period of the random oscillations showed a significant effect for finger condition, $F(2, 84) = 22.34, p < .01$. The period of the right finger in the dual-limb condition (384 ms) was significantly shorter than the period of the right finger in the single-limb condition (410 ms) and the left finger in the dual-limb condition (434 ms).

The analysis of the modal frequency and the power at modal frequency showed only a finger main effect, $F(2, 84) = 11.67, p < .01$, and a Finger × Feedback interaction, $F(2, 84) = 5.59, p < .01$, for modal frequency. The left finger in the dual-finger condition showed a higher frequency ($M = 0.53$ Hz) than the right finger in the single- (M = 0.32 Hz) and dual-finger (M = 0.30 Hz) conditions. There were strong peaks at those frequencies, but the power in the spectrum spread out from about 0–5 Hz. The broader range led to a lower mean frequency in the random as opposed to the preferred conditions.

Regularity of Movement

The condition means for ApEn in the random movement trials are shown as a function of practice in Figure 2. There was a significant effect for feedback condition on ApEn, $F(1, 6) = 12.27, p < .05$; the no-feedback condition (M = 0.40) showed more irregularity than the feedback condition.
(M = 0.29). There was also a main effect for finger condition, F(2, 84) = 4.99, p < .01. The left finger in the dual-limb condition (M = 0.36) had a higher ApEn value than the right finger in the single-limb condition (M = 0.32). The ApEn value for the right finger in the dual-limb condition was M = 0.35. The practice effect of days on ApEn was non-significant, F(4, 84) = 1.29, p > .05.

Comparison of the regularity of motion between the preferred and random movements (on the basis of the ApEn analysis) showed that the preferred movements had a greater structure in their movement signal than the random movements. The degree of irregularity produced by the random movements was a relatively low value, considering the scope of the ApEn scale. The overall mean ApEn was 0.29 for the preferred conditions and 0.35 for the random conditions.

To provide an index of the duration within a sequence of the relational structure within the random movements, we ran an autocorrelation on each random trial up to a lag of 500 data points, and the time to the first zero crossing was calculated. The only significant difference in time to first zero crossing was for the finger main effect, F(2, 84) = 4.59, p < .05. The right finger in the single-limb condition (M = 1.70 s) had a significantly longer time than the left finger under the dual-limb condition (M = 1.28 s). The mean for the right finger under the dual-limb condition (M = 1.55 s) was not significantly different from the means in the other two finger conditions. Overall, the mean times for zero crossing were of relatively short duration.

**EXPERIMENT 2**

In Experiment 2, we further examined the effects of learning to move randomly by having participants practice the task under two different information-feedback conditions than those used in Experiment 1. In Experiment 2, augmented information feedback was presented on-line as concurrent information and varied in the amount of prior information presented. In one condition, participants received augmented position–time information about all the completed trials to date. In the other condition, the augmented information was restricted to the last 10 s of the ongoing trial. There were no preferred movement trials performed in this experiment.

**Method**

**Participants**

The participants were 8 right-handed students (2 men, 6 women; mean age = 22.63 years) at The Pennsylvania State University. All participants provided informed consent prior to testing. The experimental procedures used in this study were approved by the Office of Regulatory Compliance at The Pennsylvania State University.

**Apparatus and Procedures**

The apparatus and procedures were generally the same as those reported for Experiment 1. The major difference was that no preferred oscillation trials were conducted in this experiment. In addition, given the on-line information-feedback manipulation, the participants had their eyes open throughout each trial.

There were two information-feedback conditions for the random learning trials. In one condition, the last 10 s of the position–time signal was shown in real time to the participant (scroll feedback). We presented that information by means of a sliding window presentation of the signal on the computer screen. In the other condition, the position–time signal was shown for the complete trial to date, which gradually evolved in four separate 30-s segments on the screen (all-screen feedback). There were 3 days of practice for each feedback condition, which were performed either on successive days or with no more than a 1-day gap between practice sessions.

**Results**

**Movement Space–Time Characteristics**

The measures for the distributions of the space–time characteristics of the movements were calculated and analyzed as reported for Experiment 1, except that there were no preferred movements in Experiment 2 and the practice lasted 3 days rather than 5 days. We analyzed each dependent variable reported in the following by using a 2 (feedback) × 3 (day) × 3 (finger condition) ANOVA with repeated measures on the last two variables.

The only significant effect on the mean amplitude of motion was the finger condition, F(2, 48) = 6.74, p < .01. Post hoc analysis showed that the left finger in the dual-limb condition (M = 28.89°) had a greater mean amplitude of motion than the right finger in both the dual- (M = 23.89°) and the single-limb (M = 24.88°) conditions. None of the other main effects or interactions were significant (all ps > .05).

The standard deviation of the amplitude of motion was not significant for feedback condition, F(1, 6) = 0.42, p > .05. There was a Feedback Condition × Day interaction, F(2, 48) = 5.20, p < .01. The cause of the interaction was that the variability of amplitude in the all-screen feedback condition was reduced over the three days of practice whereas the variability of amplitude was maintained at about the same level over days in the scroll feedback condition. There was a significant effect for finger condition, F(2, 48) = 6.44, p < .01. Post hoc analysis revealed that the left finger in the dual-limb condition (M = 23.26°) had a larger variability of the amplitude of motion than the right finger in the dual- (M = 20.60°) and single- (M = 21.30°) limb conditions.

The analysis of the mean period of the random motions revealed a main effect for finger condition, F(2, 48) = 14.17, p < .01, and the interaction of feedback condition and day, F(2, 48) = 4.36, p < .05. Post hoc analysis of the finger condition showed that the left finger in the dual-limb condition (M = 446 ms) had a longer mean period than the right finger in the dual- (M = 395 ms) and single- (M = 383 ms)
limb conditions. The Group × Day interaction was the result of the reduction in the mean period of the random motions over days for the all-screen feedback condition but not for the 10-s scroll feedback condition.

There were no main effects or interactions for either the modal frequency or power at modal frequency (ps > .05). The mean modal frequency across all subjects and conditions was low, at 0.29 Hz. Again, the range of frequencies for the random movements (with power above 5% of the peak power) was between 0–6.15 Hz, and that broader range produced within it a relatively low mean frequency for the random movements.

Regularities of Movements

In Figure 3, the mean ApEn values are shown as a function of feedback group and days of practice. Again, the overall level of irregularity produced was relatively low. There were no significant main effects or interactions on ApEn (all ps > .05). The mean for the all-screen feedback condition was 0.28, whereas the ApEn mean for the scroll feedback condition was 0.25.

The time to first zero crossing from the autocorrelation revealed a significant effect for finger and the Feedback Condition × Day interaction. For finger condition, the right finger in the dual-finger condition (M = 2.07 s) had a significantly longer time to zero crossing than the left finger in the dual condition (M = 1.73 s) and the right finger in the single-limb condition (M = 1.54 s), F(2, 45) = 6.72, p < .05. The reason for the interaction of feedback and day was that the time to zero crossing increased over days in the scroll feedback condition but was reduced over days in the all-screen feedback condition.

GENERAL DISCUSSION

The findings from the two experiments showed that participants did not learn to enhance the degree of movement randomness under the different feedback conditions and up to 5 days of practice. Those findings substantiate the results of previous experiments on random movements (Newell et al., in press) and extend them by showing the persistence of the boundary constraints on the production of random movement. We now examine in more detail the theoretical implications of the current findings.

The participants produced a modest level of randomness in the finger planar motion that was at about the same level as was found in a previous experiment by Newell et al. (in press). We did not conduct a dimensional analysis on the random movements here because previously we had found that a reliable estimate of the correlation dimension was not possible with the amount of data in each trial. The dimension estimate of random finger movements settled at around the value of 6–7 in the experiment of Newell et al. (in press), but we could not confirm that estimate formally here. Nevertheless, the estimate seems of about the order that might be linked to the ApEn values obtained here, and the ApEn estimates of irregularity certainly indicated that the output holds considerable structure and is significantly different from white Gaussian noise (Pierce, 1961).

A theoretical implication of that estimate of the degree of movement randomness is that the structural and functional constraints on single-limb planar motion are quite restrictive. One consequence of the low boundary-level constraints is that in motor tasks where the goal is the production of an invariant spatial–temporal property, it would seem that the control structure is required to generate a limited reduction in the degrees of freedom of movement output. In other words, there are fewer degrees of freedom to control than are implied in standard accounts of the degrees of freedom problem (Bernstein, 1967; Saltzman, 1979; Turvey et al., 1978). Those structural and functional constraints may be even more restrictive in a relative sense when movement coordination is considered in multijoint situations, but that is a topic for future research.

The participants did not use the full range of amplitudes and frequencies that they can produce while trying to move in a random sequence. Whether the effective range of movement parameterization influences the degree of randomness produced is not clear from these experiments. Furthermore, the spectral analysis of the random movements did not reveal any particular frequency profile to the spectrum. The peak power was at a low frequency primarily because there were a significant number of very slow movement segments in the sequence. Thus, these analyses did not reveal any systematic frequency properties that may contribute to the constraint on the production of random movements.

In the practice conditions used in the experiments reported here, participants were not able to induce an increment in the randomness of motion, even after 5 days of practice. Not one participant in either experiment showed a systematic increment in the randomness of movement with practice. It is, however, premature to suggest that participants cannot learn to enhance the stochastic properties of single-
limb movement output, but it is clear that the task used here does provide constraints on learning that are different than those evident in most tasks studied to date (cf. Magill, 1980; Schmidt, 1982). Furthermore, it is apparent that the degree of randomness produced from this task constraint produces a much lower level of stochasticity than is shown in the natural variation of whole-body and finger postural tremor tasks (cf. Newell & Sliufkin, 1998). The movement data in the experiments reported here all hold parallels to the findings in literature on cognition that the production of random symbol strings is difficult (Rosenberg et al., 1990; Wagenaar, 1972).

There was no difference between the information-feedback conditions in terms of influence on the randomness of movement output. Indeed, the no-information-feedback condition led to the same degree of random output as did all of the feedback conditions. Thus, the augmented information feedback used here did not facilitate performance outcome and the learning of the random task demands. It is well established that information feedback is a potent learning variable in many motor task situations (Newell, 1991; Newell et al., 1985; Swinnen, 1996). Thus, the failure to find a learning effect in this study adds further weight to the proposition that there are persistent and robust constraints on the production of random movement. In that regard, it was also the case that there was little difference between the random performance of subjects over the two experiments, which suggests that the presence of general visual information was also not helpful in the learning process. Of course, it is possible that categories of augmented information other than feedback may be more useful in learning this task (Newell, 1991), but that remains an empirical question.

In summary, the present findings provide further evidence that there are relatively tight constraints on the degrees of freedom of single-limb planar motion and that those constraints are not susceptible to change through typical learning protocols. It is possible that other learning protocols may be able to induce learning in this task, but the findings reported here indicate that the boundary constraints on intentionally moving in a stochastic fashion are persistent and not easy to change. The implication is that the control structure induces a more limited reduction in the dimensionality of the system degrees of freedom than is typically postulated in theories of movement control.

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REFERENCES


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