Exploratory Aspects of Variability in Learning a Novel Skill

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***Abstract*—Movement variability has been typically thought as detrimental, but it also plays a positive role for perception and action. One positive aspect is that it allows exploring different task solutions. Using a virtual throwing task [1], we examined how participants explore task solutions as they become more skilled. Naive subjects practiced 240 throws a day for 11 days—one group (*N*=13) had an easy target location and another (*N*=10) a difficult one. We hypothesized that participants in both groups would initially explore the task result space early in learning to find a solution and then fine-tune this solution over practice. We also hypothesized that once participants learn to reduce intrinsic noise, they would explore different solutions within the result space. Consistent with our hypothesis, participants in both groups found an initial task solution region. Only subjects in the easy target group, however, increased in variability to continue exploring the result space, as they were able to reduce their noise to a low level faster than the difficult target group. These results support the prior finding that participants initially seek most error-tolerant regions [1] and our hypothesis that exploration increases as expert participants reduce noise.**

Keywords—skill learning; variability; exploration; noise.

I. INTRODUCTION

Variability is a ubiquitous feature of human sensorimotor performance. It is generally assumed that one source of the observed behavioral variability is the intrinsic "noise" inherent to the complex neuromechanical system [2]—even as one attempts to perform the same exact movement repeatedly, the result varies from one attempt to another. Variability can also stem from intentional changes in performance strategies. It is likely that during learning a novel motor skill, both of these sources contribute to the observed variability, but with different emphasis at different stages during practice. Initial exploration has been described [1], but features of long-term exploration of task solutions are not known.

Early in learning, the inability to reliably repeat the same action due to high intrinsic noise encourages learners to seek most error-tolerant task solutions. Utilizing a framework of Tolerance, Noise, and Covariation (TNC), experimental findings from a throwing task [1] showed that such initial exploration occurred over the first two days of practice (decrease in *T*-cost). Following initial exploration, task solutions within the discovered region in result space were subsequently fine-tuned by increasing covariation between execution variables (*C*-cost) and decreasing noise (*N*-cost).

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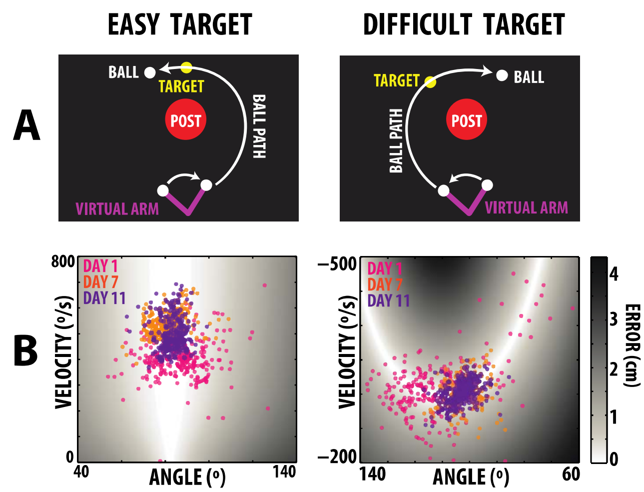

Fig. 1. **A:** Virtual environments for easy and difficult targets. **B:** Result space for the respective targets with exemplary release values for days 1, 7, and 11.

The throwing task, like many other complex motor skills, has redundancy, where multiple combinations of execution variables lead to the same result. While each learner initially honed into a region insensitive to intrisinic noise, this tolerant-region contains only a subset of all possible solutions. We hypothesized that once participants are capable of producing the same action with less intrinsic noise, they will chose to explore different, less error-tolerant regions of the result space. If so, then participants that achieved a high level of movement repeatability (low *N*-cost) after long-term training, would explore different, less error-tolerant regions of the result space that potentially lead to more risky performance.

To test this hypothesis we conducted an experiment using a virtual throwing task where subjects have to throw a ball to hit a target. Two groups practiced one target locations each: An easy target where only release angle but not its velocity determined task success; a difficult target where both angle and velocity mattered for success. The covariation of angle and velocity describes a nonlinear solution manifold. We hypothesized that both groups would decrease *T*-cost early in practice indicating exploratory behavior. We further hypothesized that participants practicing the easy target would decrease *N*-cost faster than the nonlinear manifold. Crucially, only in the easier task we expected to see more attempts at exploring alternative combinations of performance variables (angle or velocity). This should be more pronounced toward the end of the extensive practice.

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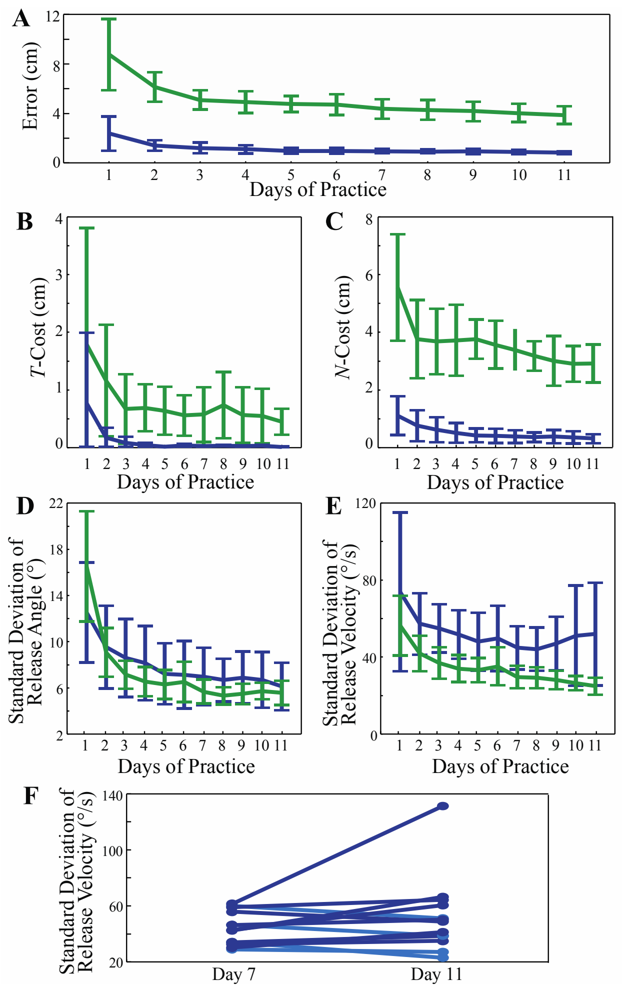

Fig. 3. Dependent measures across days of practice. Each point is the average for the easy (blue) and difficult (green) target groups across 240 throws per day. Error bars indicate one standard deviation across subjects. (A) Average error. (B) *T*-cost. (C) *N*-cost. (D) Standard deviation of release angle. (E) Standard deviation of release velocity. (F) Standard deviation of release velocity for subjects in easy target group on day 7 compared to day 11 (increasing in dark blue, decreasing in light blue).

II. Methods

A. Experimental Design

24 right-handed participants practiced the virtual throwing task (N=13 on easy target location, N=10 on difficult target location) over the course of 11 daily sessions, with 240 throws per session, for a total of 2640 throws.

B. Experimental Task

Subjects practiced a virtual throwing task based on the British pub game Skittles as described in [1]. In Skittles, a player throws a ball tethered to a center post in attempt to hit a target placed on the far side of the post from the player. In the experimental version of the task, subjects performed a single-joint rotation about the elbow on a lever arm and released a virtual ball that traversed a concentric force field to hit a target (Fig. 1A). The two execution variables, angular position and velocity of the lever arm at the time of release, fully determine the single result variable, error, for each throw. Error was defined as the minimum distance between the ball path and the target center. If the error was below 1.1cm, the target turned green to indicate a successful hit. The different possible combinations of the execution variables represent the execution space. For each point in execution space, an error value is calculated from the motion equations for the ball. The resulting error value is shown using a color scale, with lighter colors indicating lower errors (Fig. 1B).

C. Dependent Measures

1) Error: Change in task performance with practice was quantified using the result variable, error.

2) T-cost: The *T*-cost measures that expresses the performance gain that would have been achieved if the actual distribution of release angles and velocities was located in the most tolerant region of the phase space. In the case of the vertical manifold we kept the velocity constant in the estimation of *T*-cost (see [2]).

3) N-cost: The *N*-cost measures the performance gain that would have occurred if participants could decrease the spread of their variability of release angle and velocity (see [1]).

4) Standard deviation of execution variables: Variability in the the two execution variables, release angle and velocity, was used to gauge the degree of task performance consistency.

III. Results

As expected, all subjects reduced their *Error* with practice, but subjects practicing on the easy target reached a lower error level (Fig. 3A). *T*-cost decreased within the first two days for both groups, but remained slightly higher in the more difficult group (Fig. 3B). The *N*-cost also decreased in both groups, reaching a plateau in the easy, but not in the difficult group (Fig. 3C). Variability in the execution variables reached a plateau in the group learning the easy target, but kept improving into the 11th day in the group practicing the difficult target (Fig. 3D-E). Participants in the easier task, showed increased variability in the velocity standard deviation toward the end of the 11 day practice compared to day 7 (p = .06) without any loss of performance quality (Fig. 3F).

IV. Discussion

An increase in the variability of release velocity from day 7 to 11 in the easy target group likely reflects a process of intentional exploration of the result space. We suggest that in order for such exploration to be successful and not detrimental to the immediate level of performance, participants first have to reach a plateau in their ability to consistently repeat a single successful task strategy (low *N*-cost). This suggests that there may be two facets of exploration in learning a novel motor task: An initial ball-park approximation to the solution and then intentional expert-level exploration of the task performance variable combinations to further probe the solution manifold.

References

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