State Space Analysis of Human Timing

Timing Accuracy Limit is 9 ms

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***Abstract*— Understanding timing accuracy in humans is critical as it presents an important constraint on skilled motor performance. The limits intrinsic to the central nervous system, however, remain highly disputed and reported values range from 1ms to 9ms. Using a virtual throwing task that allowed precise control and measurement of task performance, this study explored the bounds of human timing accuracy in a long-term learning experiment. Eleven naive subjects practiced 240 throws per day for 11 days. We hypothesized that subjects (1) cannot control timing more accurately than 9 ms, and (2) shape their hand trajectory to become less sensitive to timing inaccuracy. A state space analysis of timing developed by [1] was used to quantify change in timing accuracy and sensitivity of the hand trajectory with practice. Consistent with our hypothesis, results revealed that subjects reached a limit in their timing accuracy at approximately 9.5 ms. Subjects also showed a monotonic increase of time insensitivity of the hand trajectory. These results support the prior finding of [1] that timing accuracy is a limiting factor in skilled performance, and that humans shape their movements to compensate for this intrinsic limitation.**

***Keywords*— motor skill learning; timing; precision; variability**

I. Introduction

In the current literature, the resolution of human timing is still debated. Hore and Watts [2] report that highly skilled baseball pitchers release the ball with a timing precision as low as 1ms. Others argued that subjects vary the release time in order to compensate for errors in their hand movements [3]. One methodological problem that makes comparison across studies difficult is what reference is used to measure timing in functional hand movements. Using a novel state space analysis in a virtual throwing task, Cohen and Sternad [1] found that timing precision is approximately 9 ms, both in novice and expert throwers. Their results highlight that instead of increasing precision of the ball release, humans increase throwing accuracy by shaping their hand trajectory to compensate for their intrinsic timing limitations.

The present study aimed to further corroborate the limitations of human timing precision. To test and generalize the previous results the experiment used the same virtual throwing task but with a modified state space by changing the location of the throwing target. The goal was to test whether the state space analysis of timing still yielded the same results as [1]. We hypothesized that subjects reach a timing accuracy limit of 9 ms and shape their hand trajectory to accommodate for variability in release timing over practice.

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II. Methods

A. Experimental Design

11 right-handed students from Northeastern University practiced the virtual throwing task over the course of 11 daily sessions, with 240 throws per session, for a total of 2640 throws. None had any prior experience with the experimental task. All participants gave informed written consent before the experiment and received monetary compensation upon completion. The experimental protocol was approved by the Institutional Review Board of Northeastern University.

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. In the experimental version of the task, subjects were instructed to throw the ball to hit the center of a target skittle in the virtual scene. The subject's right arm was secured to a horizontal lever arm to constrain movement to a single-joint elbow rotation in the horizontal plane (Fig. 2A). This horizontal rotation of the lever arm was measured with a potentiometer. The subject's right hand gripped a wooden ball fixed to the distal end of the lever arm. The subject released the virtual ball by removing his/her index finger from a force resistor attached to the wooden ball.

The virtual scence showed a top down view of the arm rotating in real-time, a ball, a post, and a target, all displayed on a rear project screen in front of the subject (Fig.2B). Upon release, the ball traversed an elliptical path in the virtual scene for 1.5s as determined by two execution variables: the angular position and velocity of the lever arm at the time of release. The result variable, error, was defined as the minimum distance between the ball path and the target center. If the error was below a threshold of 1.1cm, the target changed color to indicate a successful hit.

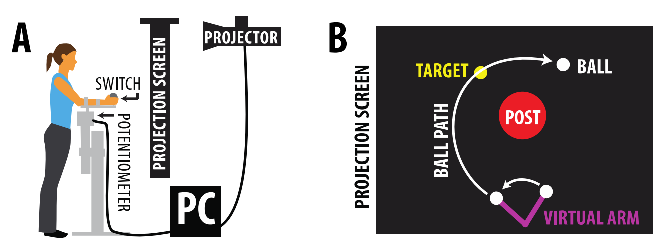

Fig. 1. Experimental Setup. A: Schematic of subject and virtual environment. B: The virtual display showed a top-down view of the ball, center post, and the target in front of the subject.

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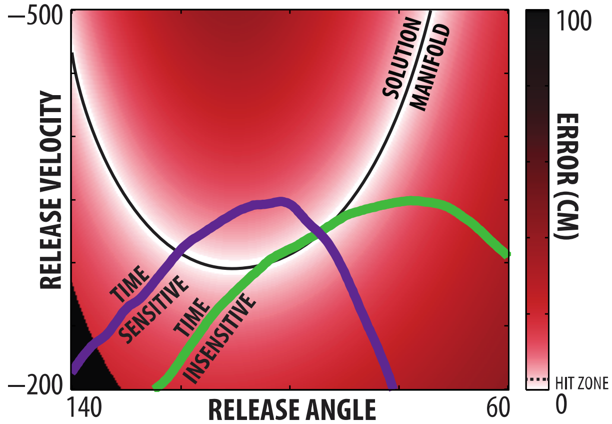

Fig. 2. Exemplary trajectories in execution and result space. The purple line represents a time-sensitive hand trajectory, the green line represents a time-insensitive trajectory.

C. *Result Space and Solution Manifold*

The result or error of each throw is fully determined by two execution variables: angular position and velocity at release. For each point in execution space, an error value is calculated from the motion equations for the ball path. Using color for the resulting error value, Figure 2 depicts the execution and result space; lighter colors indicate lower errors. Specifically, the thin black line indicates the zero-error solutions, the solution manifold. The areas in white indicate the "hit zone", the angular position and velocity combinations that lead to a target hit, albeit not zero error.

The green line in Figure 1 illustrates a time-insensitive hand trajectory: the trajectory travels along the solution manifold, where the timing of ball release becomes irrelevant, as any release will achieve a successful hit. Conversely, the purple line exemplifies a time-sensitive trajectory, as precise release timing is needed to successfully hit the target.

To test the generality of previous results, this study used a different location of the target which yields a different result space than [1].

D. *Dependent Measures*

To quantify the strategies and timing, the following dependent measures were calculated (see [1]).

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

2) Time from Ideal Release: Timing accuracy was quantified as the time difference between actual and ideal release time; the latter is the time that yielded the lowest possible error, for a given trajectory.

3) Time in Hit Zone: The amount of time the trajectory spent in the hit zone of the result space quanitified its time-sensitivity: the longer the time in the hit zone, the less time-sensitive the trajectory.

4) Integrated Error: The integral of the errors within +/- 13ms of the ideal release time quanitified the time-sensitivity of the trajectory: the lower the integrated error, the less time-sensitive the trajectory.

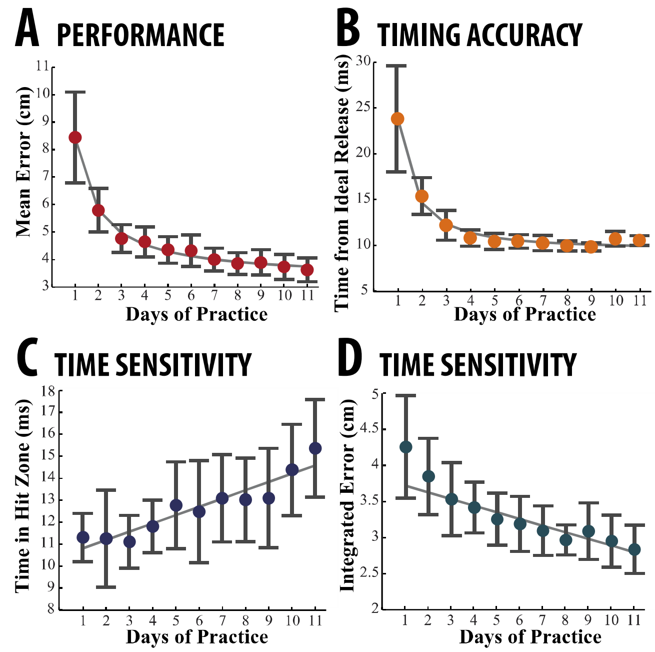

Fig. 3. Dependent measures across days of practice. Each point is the average across 240 throws per day. Error bars indicate +/- 2 standard errors across subjects. (A) Average error, fitted with a power law function. (B) Average timing accuracy, fitted with a with power law function. (C) Average time in hit zone, fitted with a linear function. (D) Average integrated error, fitted with a linear function.

III. Results

As expected, subjects reduced their throwing *Error* with practice, following a power law (R^2=.99, Fig.3A). *Time from Ideal Release*, the measure of timing accuracy, similiarly followed a power law (R^2=.99) reaching an asymptote at 9.5ms (Fig. 3B). The *Time in Hit Zone* linearly increased with practice (R^2=.88), indicating that trajectories became increasingly less time sensitive (Fig.3C). This result was also supported by a linear decrease in the *Integrated Error* (R^2=.91), (Fig. 3D).

IV. DISCUSSION

The experimental results further support the findings of [1] corroborating that subjects have a timing accuracy limit of approximately 9ms. The trajectory measures quantify that they shape their hand trajectory to become less time-sensitive with practice. Most importantly, while timing accuracy asymptotes, time-sensitivity continues to change monotonically. This suggests that when reaching the limit of timing accuracy, subject continue to improve through hand trajectory shaping.

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