The Earlier You Know, the Smoother You Act

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Introduction

Interception is a fundamental aspect of daily activities, such as catching a moving ball in various sports. In ball-catching tasks, the endpoint of a movement can lie anywhere along the target's trajectory [1]. Toss juggling exemplifies a motor skill that requires rhythmic catching and throwing of objects under spatial and temporal constraints. During the catching phase, a juggler's hands begin moving even before fully estimating the target's trajectory, with adjustments made to the targeted position during the movement. Simultaneously, the juggler must coordinate the act of throwing the ball already in hand.

This study investigates anticipatory behavior in juggling, offering insights into movement planning during this activity. Specifically, we compare two juggling conditions: solo 3-ball cascade juggling (condition 1) and dyadic 3-ball cascade juggling (condition 2). Following an approach in [2], our goal is to demonstrate that jugglers can predict a ball's trajectory earlier in solo juggling compared to dyadic juggling scenarios, due to predictions based on internally available information at ball release.

Methods

A total of 18 jugglers participated in the experiment. The jugglers were chosen based on the inclusion criteria that they are able to comfortably sustain a 3 ball cascade pattern for longer than 20 s. All the jugglers were either ambidextrous or right-handed. Handedness was assessed based on the participants' preferred hand for daily activities and writing. The experiment had two conditions. In the first condition, the juggler had to perform a regular 3 ball cascade pattern (*solo juggling*), and in the second condition, the juggler was paired with another juggler with whom they performed a side-to-side shared 3 ball cascade pattern (*dyadic juggling*). For the second pattern, both the jugglers stood next to each other facing forward, and the juggler (*partner*) standing to the left of the other juggler used their left hand, while the other juggler (*initiator*) used their right hand. After each trial, the jugglers switched places, i.e., the *initiator* of the previous trial became the *partner* in the next trial, and vice-versa. In both the conditions, each trial started with the first throw from the right hand (specifically, in the *dyadic juggling* case, by the *initiator*).

In the experiment, participants first performed a 3-ball cascade pattern (Condition 1), followed by the dyadic condition (Condition 2), standing 50 cm apart. Each trial lasted until the experimenter said "STOP!" or if the juggling pattern collapsed within 20s, whichever happened earlier. No instructions on speed or height were given, and all trials started with participants standing in the same spot.

This study explores to which extent anticipation of a ball's trajectory based on internally available information during the throw affects the following catch of that particular ball. Using the method proposed in [2], we examined how predictions based on information from the throwing hand affect the timing of the catching hand's movements. By leveraging the empirical principle that goal-directed trajectories exhibit minimal jerk [3][4], we investigated how early jug-

glers achieve smooth, goal-directed hand movements in solo juggling (condition 1) compared to when they lack throwing information from the opposite hand (condition 2). This approach evaluates the shortest distance between the hand and the ball's future trajectory over time. Using this one-dimensional trajectory data, the smooth approximation is identified by fitting a minimum jerk trajectory as an analysis tool, where jerk is defined as the third derivative of position with respect to time. A minimum jerk trajectory, J_{min}, minimizes the sum of the squared jerk values along the object's path between an initial time t_o and a final time t_f.,

Results

Our findings align with our hypothesis, demonstrating that jugglers can predict a ball's trajectory earlier when they have proprioceptive feedback from the throwing hand (condition 1). In contrast, their ability to anticipate the trajectory is reduced when this proprioceptive information is unavailable (condition 2). In condition 2, the smooth (goal-directed movement) phase is delayed by approximately 43% compared to condition 1. This highlights the critical role of sensory information from the throwing hand in facilitating early prediction and coordination during juggling.

Discussion

The goal of this study was to demonstrate that proprioceptive feedback from the juggler's throwing hand plays a critical role in determining the timing of the catching hand's movement. In a juggling task, where the ball can be caught at any point along its parabolic trajectory, accurate and early prediction of the ball's path is essential for maintaining stability in the juggling pattern. Our findings further highlight the relationship between sensory input and motor planning, underscoring the importance of proprioceptive information in enabling smoother and more efficient hand movements in complex dynamic tasks like juggling.

Dyadic juggling, in contrast to solo juggling, adds significant complexity to the task. The absence of proprioceptive information for the incoming balls, combined with a sole reliance on visual feedback, likely results in a delay in identifying the target. Additionally, other factors may also contribute to this delayed identification. It is well-established that the ability to catch a ball depends not only on tracking the ball but also on observing the complete throwing action of the partner, in addition to the ball's flight [5]. Future research will further explore this aspect.

Although juggling is theoretically an infinite-horizon task, it can be broken down into a series of finite-horizon tasks, alternating between catching and throwing. During this sequence, the juggler must not only ensure an accurate throw to the other hand but also predict the trajectory of the incoming ball as early as possible, which the same hand will subsequently catch. Further investigation is needed to explore in greater detail the predictive and prospective strategies jugglers employ to maintain the stability of their juggling patterns.

References

[1] Cesqui, B., d'Avella, A., Portone, A., & Lacquaniti, F. (2012). Catching a ball at the right time and place: individual factors matter. *PLoS one, 7(2), e31770.*

[2] Slupinski, L., de Lussanet, M. H., & Wagner, H. (2018). Analyzing the kinematics of hand movements in catching tasks—An online correction analysis of movement toward the target's trajectory. *Behavior Research Methods, 50(6), 2316-2324.*

[3] Hogan, N. (1984). An organizing principle for a class of voluntary movements. *Journal of neuroscience, 4(11), 2745-2754.*

[4] Flash, T., & Hogan, N. (1985). The coordination of arm movements: an experimentally confirmed mathematical model. *Journal of neuroscience, 5(7), 1688-1703.*

[5] Maselli, A., De Pasquale, P., Lacquaniti, F., & d'Avella, A. (2022). Interception of virtual throws reveals predictive skills based on the visual processing of throwing kinematics. *Iscience*, *25(10)*.