



**HAL**  
open science

## 'Mixed' control for perception and action: timing and error correction in rhythmic ball-bouncing

Isabelle Siegler, Christophe Bazile, William H. Warren

► **To cite this version:**

Isabelle Siegler, Christophe Bazile, William H. Warren. 'Mixed' control for perception and action: timing and error correction in rhythmic ball-bouncing. *Experimental Brain Research*, 2013, sous presse. 10.1007/s00221-013-3475-7. hal-00796778

**HAL Id: hal-00796778**

**<https://hal.science/hal-00796778>**

Submitted on 5 Mar 2013

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

‘Mixed’ Control for Perception and Action:  
Timing and Error Correction in Rhythmic Ball-Bouncing

Siegler, I.A.<sup>1</sup>, Bazile, C.<sup>1</sup>, Warren, W.H.<sup>2</sup>

Affiliation of authors

<sup>1</sup>UR CIAMS (EA 4532), Univ Paris-Sud, Orsay, France

<sup>2</sup>Department of Cognitive, Linguistic, and Psychological Sciences, Brown University, USA

Corresponding author:

Isabelle A. Siegler

Univ Paris-Sud, UR CIAMS (EA 4532)

Orsay,

F- 91405 Cédex

E-Mail: [isabelle.siegler@u-psud.fr](mailto:isabelle.siegler@u-psud.fr)

Phone: 33 1 69 15 43 11

Fax: 33 1 69 15 62 22

## Abstract

The task of bouncing a ball on a racket was adopted as a model system for investigating the behavioral dynamics of rhythmic movement, specifically how perceptual information modulates the dynamics of action. Two experiments, with sixteen participants each, were carried out to definitively answer the following questions: How are passive stability and active stabilization combined to produce stable behavior? What informational quantities are used to actively regulate the two main components of the action – the timing of racket oscillation and the correction of errors in bounce height? We used a virtual ball-bouncing set-up to simultaneously perturb gravity ( $g$ ) and ball launch velocity ( $v_b$ ) at impact. In Experiment 1, we tested the control of racket timing by varying the ball's upward half-period  $t_{up}$  while holding its peak height  $h_p$  constant. Conversely, in Experiment 2, we tested error correction by varying  $h_p$  while holding  $t_{up}$  constant. Participants adopted a mixed control mode in which information in the ball's trajectory is used to actively stabilize behavior on a cycle-by-cycle basis, in order to keep the system within or near the passively stable region. The results reveal how these adjustments are visually controlled: the period of racket oscillation is modulated by the half-period of the ball's upward flight, and the change in racket velocity from the previous impact (via a change in racket amplitude) is governed by the error to the target.

(228 words)

Keywords:

Perception and action, visual control, rhythmic movement, dynamical systems

# Introduction

## *Living in the material world*

Biological systems live in a material world and must interact with its physical properties. This can be viewed as an obstacle to carrying out functional tasks, or as part of the solution that simplifies the control problem. The fundamental question underlying the present research is how biology exploits physics to order behavior. There is growing evidence that perceiving-acting systems capitalize on physical dynamics in order to generate stable patterns of behavior (Turvey 1990). At the same time, to avoid getting locked into rigid action patterns, they use perceptual information to modulate those dynamics in order to achieve adaptive flexibility (Warren 2006). Precisely how passive dynamics is combined with active control to generate stable, adaptive behavior is a general problem in the study of perception and action. In this article we argue for a control regime that we call ‘mixed control’ as a general solution to this problem.

There are many real-world examples of this combination of passive stability and active control. For instance, the morphology of the human musculoskeletal system realizes a dynamically stable and energy-efficient solution for bipedal walking (Kuo 2007), which has recently inspired the design of passive dynamic robots (Collins et al. 2005). This design simplifies the control problem from one of actively controlling all biomechanical degrees of freedom to one of tweaking the passive dynamics of the system.

We adopted the task of bouncing a ball on a racket as a model system for investigating the behavioral dynamics of rhythmic movement (Warren 2006), specifically how perceptual information modulates the dynamics of action. The physics of ball-bouncing is well understood and exhibits a passively stable solution for period-1 bouncing (in which the ball’s flight period is equal to one racket period and bounces to a constant height). By using a

virtual ball-bouncing set-up, visual information about the ball’s trajectory can be manipulated to probe the relation between passive dynamics and active control. The present study aimed to definitively answer three questions. First, how are passive stability and active stabilization combined to produce stable behavior? Further, what informational quantities are used to actively regulate the two main components of the action – the timing of racket oscillation and the correction of errors in bounce height?

### *Dynamics of ball bouncing*

Schaal et al. (1996) and Dijkstra et al. (2004) modeled the ball-racket system, analyzed its nonlinear stability properties, and demonstrated its relevance to motor control. In these models, the ball falls with gravitational acceleration  $g$ , racket motion is periodic (or harmonic), and the ball-racket system is characterized by its coefficient of restitution  $\alpha$  (i.e. the “bounciness” of the ball with a constant racket). By means of local and non-local stability analyses, the authors showed the existence of a *passively stable* regime, in which small perturbations or errors in ball motion will die out after several racket cycles, without active error correction. Specifically, if the falling ball is hit during racket upswing and if racket acceleration at impact  $a_r$  is negative and satisfies the following relationship between  $g$  and  $\alpha$ :

$$\frac{-2g(1+\alpha^2)}{(1+\alpha)^2} < a_r < 0$$

then the ball will spontaneously relax back to its original limit-cycle trajectory. The ball-bouncing system is thus self-stabilizing with respect to its flight period and bounce height. From the perspective of perceptual-motor control, exploiting passive stability obviates the need for active error correction, for bouncing is stable even for a blind open-loop system with no perceptual input.

Initial reports confirmed that experienced participants tend to bounce in the passively stable regime, with negative impact accelerations clustered in the maximally stable range (Schaal et al. 1996; Sternad et al. 2001). As expected, the variability of impact acceleration and ball amplitude were also lowest in the maximally stable range. With practice, impact accelerations became progressively negative over trials and converged to the maximally stable region (Sternad et al. 2000). This evidence indicates that actors exploit passive stability, consistent with the passive stabilization hypothesis.

However, later studies revealed that participants can *actively stabilize* bouncing outside the passive region (de Rugy et al. 2003; Wei et al. 2007; Morice et al. 2007), implying that they also take advantage of perceptual information to control the racket oscillation. When  $\alpha$  was perturbed, altering the flight time and peak height of the ball's trajectory, steady-state bouncing was reestablished faster than predicted by passive relaxation alone, and racket adjustments were proportional to the perturbation magnitude (de Rugy et al. 2003; Wei et al. 2007). Wei et al. (2007) concluded that participants used a “blend” of active and passive control. However, de Rugy et al. (2003) did not test small perturbations, and neither study tested perturbations of  $g$ , which alter the relation between ball flight time and peak height.

#### *How are passive stability and active control combined?*

To characterize how passive stability and active stabilization might be combined, Siegler et al. (2010) described four candidate control modes. At the extremes are pure *passive control* (open-loop), which relies solely on passive self-stabilization without perceptual input, and pure *active control* (closed-loop), perceptual control alone without reference to passive stability. Examples of the latter include the ‘mirror algorithm’ for robot bouncing (Bühler et al. 1994), in which the racket velocity symmetrically mirrors the ball velocity, and optimal control solutions based on the ball's trajectory (Kulchenko and Todorov 2011). On the *hybrid*

*control* hypothesis, small perturbations are passively stabilized while large perturbations outside the passive region are actively stabilized. This implies a threshold at the stability boundary where active adjustments are initiated, depending on the magnitude of the perturbation. The *mixed control* hypothesis proposes that active stabilization exploits the passive physics of the task. On this view, bouncing is perceptually controlled on each cycle in order to keep the system in or near the passively stable region, thereby reducing the magnitude of racket adjustments and increasing the stability of behavior.

Siegler et al. (2010) provided evidence that participants regulate racket oscillation using mixed control. By suddenly changing  $g$  to a new value at the peak of the ball's flight, or changing  $\alpha$  at impact, they found very rapid racket adjustments, beginning in the first racket cycle following the transition and relaxing to a new stable state within two cycles after a change in  $g$  or three cycles after a change in  $\alpha$ . More importantly, such adjustments occurred after both stabilizing and destabilizing transitions, contrary to the hybrid control hypothesis. The findings supported a mixed control mode, in which actors take advantage of both passive stability properties and active control to achieve stable, adaptive behavior. The first aim of the present study is to provide a further test of the control mode by parametrically varying the magnitude of discrete perturbations in  $g$  and  $\alpha$ .

#### *How is racket timing visually controlled?*

How might mixed control be implemented in rhythmic ball-bouncing? There are two main components to the task: controlling the timing of ball-racket impact to keep bouncing in or near the passive region, and controlling the velocity of ball-racket impact to stabilize the bounce height at the target (error correction). For the control of timing, Siegler et al. (2010) identified three optical variables in the ball's trajectory that are informative about the time of

the ball's return to the previous impact height, and thus could be used to regulate the period and phase of racket oscillation (Fig. 1a):

(i) *Launch velocity*: Assuming that  $g$  is known, the ball's total flight time (period  $T_b$ )

$$\text{is specified by its launch velocity } v_b: T_b = 2(v_b/g)$$

(ii) *Peak height*: Given that  $g$  is known, the duration of the ball's descent, and hence

$$\text{the total flight time, is specified by its peak height } h_p: T_b = 2\sqrt{2h_p/g}$$

(iii) *Half-period*: As long as  $g$  is constant during the ball's flight, the duration of its ascent ( $t_{up}$ ) is equal to the duration of the ensuing descent ( $t_{down}$ ), and hence the ball's upward half-period specifies the total flight period, regardless of the value of

$$g: T_b = 2t_{up}$$

To dissociate these variables and test their influence on racket period ( $T_r$ ), Siegler et al. (2010) changed  $g$  to a new value when the ball reached its peak height. This altered the relation between peak height  $h_p$  and the ball's descent  $t_{down}$ , as well as the relation between the next launch velocity  $v_b$  and the ball's flight period  $T_b$ , while keeping  $t_{up} = t_{down}$  on subsequent bounces. Racket period correlated highly with  $t_{up}$  ( $r = 0.61$  to  $0.91$ ), but it also correlated with  $h_p$  in one condition ( $r = 0.77$ ). Siegler et al. (2010) concluded that racket period is likely regulated by the duration of the ball's upward half-period, the only variable among the three that does not depend upon a known  $g$ . The second aim of this paper is to dissociate these informational variables further, by perturbing  $g$  and  $\alpha$  (or equivalently, launch velocity  $v_b$ ) at impact in order to manipulate the duration of  $t_{up}$  while holding  $h_p$  constant.

### *How is error correction visually controlled?*

In addition to the control of impact timing, participants must correct for bounce error ( $\varepsilon$ ) from the target height. The key racket variable that determines the ball's peak height  $h_p$  is the racket velocity at impact ( $v_r$ ), given the ball's impact velocity ( $v_b$ ). The third aim of the



present study is thus to understand how racket velocity is visually controlled for error correction. Two main hypotheses are compared.

Ronsse and Sternad (2010; Ronsse et al. 2010) proposed that the peak height of the ball ( $h_p$ ) is used to compute the absolute racket velocity ( $v_r$ ) required on the next impact; we will call this the *absolute* hypothesis. The authors analyzed ball-bouncing as combining continuous rhythmic actuation of the racket with the control of discrete impact events, and accordingly developed a two-layer model within an optimal control framework (Todorov and Jordan 2002). In the first discrete layer, the ball's peak height is used to determine its landing velocity, which in turn is used to compute the exact racket velocity required to hit the ball to the target height. The second continuous layer then smoothly drives the racket to this desired state. However, this hypothesis assumes a known  $g$ , whereas Siegler et al. (2010) showed that accurate bouncing is recovered in only two cycles after a change in  $g$ .

Wei et al. (2008) observed that racket impact velocity was an inverse linear function of the preceding bounce error, and interpreted the negative slope as a feedback gain. However, this relation was weak for a control variable, with  $R^2$  values between 0.2 and 0.3 (depending on  $\alpha$ ). Within an oscillator framework, Siegler et al. (2010) argued that impact velocity is a consequence of the racket amplitude, and assumed the latter would be visually controlled. However, the correlation of racket amplitude with the preceding error (ball peak height  $h_p$ ) was virtually nil, and they could not identify an effective control law. Thus, it is not clear that either absolute racket velocity or racket amplitude are visually controlled.

In order to avoid under-specified control variables, Warren (1988) suggested that information might be used to regulate the *change* in the value of a control variable rather than its absolute value. The *relative* hypothesis thus proposes that bounce error is used to control the change in racket velocity from the previous impact ( $\Delta v_r$ ), in order to compensate for the error. Specifically, when participants see an overshoot ( $\varepsilon > 0$ ) they should produce a lower

racket velocity than on the previous impact ( $\Delta v_r < 0$ ), and when they see an undershoot ( $\varepsilon < 0$ ) they should generate a higher impact velocity than before ( $\Delta v_r > 0$ ). A simple linear relationship between  $\varepsilon$  and  $\Delta v_r$  could account for error correction, and its slope could be rapidly retuned after a change in  $g$ ,  $\alpha$ , or target height. To test these hypotheses, we isolated bounce error  $\varepsilon$  by perturbing  $g$  and  $v_b$  at impact in order to manipulate the ball's peak height  $h_p$ , while holding its upward flight time  $t_{up}$  constant.

In sum, to determine how the two main components of action are visually controlled, we used a virtual ball-bouncing set-up to simultaneously perturb  $g$  and  $v_b$  at impact. In Experiment 1, we varied the ball's upward half-period  $t_{up}$  while holding its peak height  $h_p$  constant, and conversely in Experiment 2, we varied  $h_p$  while holding  $t_{up}$  constant. We find that racket movement is actively controlled on a cycle-by-cycle basis at all perturbation magnitudes, contrary to hybrid control but consistent with mixed control. To control the timing of oscillation, racket period  $T_r$  is modulated by the ball's upward half-period  $t_{up}$ , while to perform error correction, the change in racket velocity from the previous impact  $\Delta v_r$  is regulated by bounce error  $\varepsilon$ .

-----*Insert Figure 1 about here* -----

## Experiment 1: Visual control of racket timing

The dual purpose of Experiment 1 was to identify the control mode of rhythmic bouncing, and to test the information ( $t_{up}$  or  $h_p$ ) used to control racket period. To dissociate these variables, the normal physical relation between the ball's launch velocity, flight duration, and peak

height was altered by perturbing  $v_b$  and  $g$  at impact for one-half cycle. This allowed us to vary  $t_{up}$  while holding  $h_p$  constant, and to measure the resulting racket adjustment. Graded perturbations were applied by randomly sampling a continuous range of  $v_b$  values. The mixed control hypothesis predicts that racket adjustments will be a monotonic function of perturbation magnitude, whereas the hybrid control hypothesis predicts they will only be initiated when the perturbation exceeds the stability boundary. If racket period is controlled by the ball's upward half-period, then  $T_r$  should be more strongly correlated with  $t_{up}$  than with  $h_p$  or  $v_b$ .

## **Methods**

### *Participants*

Sixteen participants were tested in Exp 1 ( $25.2 \pm 4.3$  years). None had previously participated in a bouncing experiment or had extensive practice with the task, so they were considered novice bouncers. The protocol was approved by the local ethics board (Comité éthique, Université Paris-Sud), and participants provided written informed consent.

### *Apparatus*

The virtual ball-bouncing setup (Fig. 2) was previously described in Morice et al. (2007) and Siegler et al. (2010). Participants stood 1.5 m in front of a rear-projection screen with an LCD projector (50 Hz), holding a table tennis paddle in their preferred hand (the physical racket). Racket position was measured by an electromagnetic sensor (Flock of Birds, Ascension Technologies) at a sampling rate of 120 Hz, and used to compute the vertical position of the virtual racket (a horizontal bar on the screen) and its interaction with the virtual ball (a disk 0.04 m in diameter). The paddle could be moved freely in three

dimensions, but participants were asked to keep it horizontal and to perform movements in the vertical dimension only. A sheet of cardboard positioned horizontally at neck level prevented them from seeing the racket once the experiment began. The task was to bounce the virtual ball to a target (a horizontal line) at a height  $h_T$  of 0.65 m with respect to a zero racket position, which was measured at the beginning of each session by asking the participant to hold the racket horizontally with the elbow flexed at  $90^\circ$ . A sound was played at contact between the virtual racket and the ball. Total latency was measured at 30ms (Morice et al. 2008).

-----*Insert Figure 2 about here* -----

### *Procedure*

Participants were instructed to repeatedly bounce the virtual ball to the target height. They began with twelve 40s “steady-state” familiarization trials, followed by twenty-four 40s “perturbation” test trials. During familiarization trials,  $g$  and  $\alpha$  were constant at  $9.81 \text{ m/s}^2$  and  $0.42$ , respectively, and launch velocity  $v_b$  was unperturbed. On test trials, ball kinematics were perturbed every 5 cycles on half the trials and every 6 cycles on the other half; trials were presented in a random order to minimize anticipation. During unperturbed cycles,  $g$  and  $\alpha$  were also set at  $9.81 \text{ m/s}^2$  and  $0.42$ , respectively.

### *Perturbations*

Ball and racket variables are defined in Fig. 1a. For the ball, a bounce was defined by two successive impacts, where subscript ‘0’ refers to the flight preceding the perturbed impact and subscript ‘1’ refers to the perturbation and the subsequent flight. For the racket, a cycle was defined by two successive peak racket positions, where  $C_0$  refers to the racket cycle that

contained the perturbed impact,  $C_1$  refers to the cycle that immediately followed the perturbation, and so on.

To dissociate the ball's upward flight duration ( $t_{up}$ ) from its peak height ( $h_p$ ), we introduced coordinated perturbations in the ball's launch velocity  $v_{bl}$  and  $g_I$  at impact for one half-cycle, so that  $t_{up1}$  varied while the amplitude of the ball's flight ( $H_I$ ) remained unchanged (Fig. 1b); consequently, the peak height  $h_{p1}$  was unaffected by the perturbation. The magnitude  $x$  of the  $v_{bl}$  perturbation was selected randomly so that the new launch velocity  $v_{bl}'$  varied within  $\pm 25\%$  of its original value:  $v_{bl}' = v_{bl} (1+x)$ , where  $x$  was in the range  $[-0.25, 0.25]$ . To keep the ball amplitude  $H_I$  constant despite the perturbation, a new value of gravity  $g'$  was applied for one-half cycle:  $g_I' = (v_{bl}')^2/2H_I = g(1+x)^2$ . As a consequence, the duration of the ball's ascent was modified:  $t_{up1}' = t_{up1}/(1+x)$ . In other words, if  $v_{bl}$  was increased ( $x > 0$ , "positive magnitudes") then  $g$  was increased to keep the ball amplitude constant and consequently  $t_{up1}$  decreased; and vice versa for "negative magnitudes" ( $x < 0$ ). At the peak of ball flight, the value of  $g$  was reset to the reference value of 9.81, so the duration of ball descent  $t_{down1}$  was unaffected by the perturbation.

The resulting perturbations in the ball upward motion ( $v_{bl}$  and  $t_{up1}$ ) were binned into ten categories depending on the magnitude of the perturbation of  $v_{bl}$  (Mag<sub>-5</sub>, Mag<sub>-4</sub>, ..., Mag<sub>5</sub>). For example, Mag<sub>-5</sub> corresponds to -25.0% to -20.1% perturbations of  $v_{bl}$ , Mag<sub>-4</sub> corresponds to -20.0% to -15.1% perturbations, and Mag<sub>5</sub> corresponds to +20.1 to +25.0% perturbations. Due to the nonlinear relationship between  $v_b$  and  $t_{up}$ , the relationship between perturbation magnitude and  $t_{up1}$  (and therefore with ball's total flight  $T_{bl}$ ) was also nonlinear (see Fig. 3a). Mag<sub>-5</sub> corresponds to an expected 14.5% increase of racket period  $T_{r1}$ , whereas Mag<sub>5</sub> corresponds to an expected -9.18% decrease.

### *Data reduction and analyses*

A total of 2570 perturbations were recorded in the 5-cycle trials, and 2077 perturbations in the 6-cycle trials. The raw time series of racket position were filtered with a second-order Butterworth filter using a cut-off frequency of 12 Hz. Filtered position was then differentiated to yield racket velocity, and differentiated again to yield racket acceleration. Dependent variables were selected to measure task performance, racket oscillation, and ball/racket impact. Performance was characterized by the error in bouncing to the target ( $\varepsilon$ ) defined as the difference between the midpoint of the ball at its peak position and target height. Racket oscillation was characterized by the following variables: cycle period ( $T_r$ ), defined as the time between two successive peak racket positions, and the duration of the downswing ( $T_{rdown}$ ) and upswing ( $T_{rup}$ ). For each subject, means of the dependent variables were computed for each perturbation magnitude and analyzed using repeated measures ANOVAs.

Informational variables included  $t_{up}$ ,  $t_{down}$ ,  $h_p$ ,  $v_b$ , as well as  $\varphi_{BMax}$ , the phase in the racket downswing at which the ball reached peak height. The strength of the relationship between an informational variable and a racket variable was determined by computing a Pearson's correlation for each participant on data from all perturbations. These individual  $r$  values were transformed to Fischer's  $z$  values, the group mean was computed, and then it was transformed back into a mean  $r$  value. Individual  $r$  values were compared using Williams-Hotelling t-tests for the difference between two correlated correlation coefficients.

## **Results**

Positive perturbations destabilized bouncing, whereas negative perturbations were stabilizing.

Yet in both cases we observed rapid racket adjustments that were proportional to the

perturbation magnitude and recovered a constant bounce height in only 1 cycle. This pattern of results is indicative of mixed control, in which racket motion is actively regulated on every cycle whether perturbations are large or small, destabilizing or stabilizing. In addition, the only optical variable that correlated highly with racket period was the upward half-period of the ball's flight, indicating that racket timing is visually regulated by the ball's upward flight time. We describe each of the results in detail.

-----*Insert Figure 3 about here*-----

*Positive perturbations were destabilizing, negative perturbations were stabilizing*

Mean racket acceleration at the pre-perturbation impact ( $C_0$ ) was  $1.73 \pm 0.31 \text{ m.s}^{-2}$ , slightly above the stable range, as is typical of novice bouncers (Morice et al. 2007). This implies that positive perturbations were destabilizing, because they produced a shorter  $t_{up1}$  and would result in an earlier impact with a higher racket acceleration (if uncorrected), whereas negative perturbations were stabilizing, because they produced a longer  $t_{up1}$  and a later impact with a lower acceleration. Indeed, despite partial compensation in the first racket cycle, the next impact acceleration ( $C_1$ ) was shifted in the positive direction (away from the stable region) following positive perturbations, and shifted in the negative direction (toward the stable region) after negative perturbations (Fig. 3). This confirms that positive perturbations were destabilizing while negative perturbations were stabilizing.

*Rapid recovery time*

To determine how quickly performance recovered from the perturbation, we analyzed bounce error  $\varepsilon$  over cycles separately for positive and negative perturbations. The results indicate that: (1) participants rapidly stabilized bounce height, within the first racket cycle after the perturbation in nearly all cases; (2) regardless of perturbation magnitude,

performance always recovered to baseline levels before the next perturbation (in  $C_5$  or  $C_6$ ). Specifically, for positive (destabilizing) perturbations, a two-way repeated measures ANOVA (6 cycles  $\times$  5 magnitudes) on error yielded no significant effects. Given that the first ball peak height after the perturbation ( $h_{p1}$ ) was kept unchanged, this indicates that performance recovered by the second peak ( $h_{p2}$ ), implying a recovery time of one racket cycle ( $C_1$ ). For negative (stabilizing) perturbations, a similar ANOVA revealed a significant main effect of cycle,  $F(5, 75) = 5.74$ ,  $p < 0.001$ ,  $[\eta]^2 = 0.28$ , and perturbation magnitude,  $F(4, 60) = 4.65$ ,  $p < 0.01$ ,  $[\eta]^2 = 0.24$ , but no interaction,  $F(20, 300) = 1.09$ ,  $p = 0.35$ ,  $[\eta]^2 = 0.07$ . Post-hoc Tukey tests confirmed that the first peak height ( $h_{p1}$ ) did not differ from the pre-perturbation peak ( $h_{p0}$ ), as expected. The only subsequent deviations occurred for the largest perturbation (Mag. 5), when  $h_{p2}$  and  $h_{p3}$  errors differed from  $h_{p0}$ ,  $p = .001$  and  $p = .006$ , respectively. Thus, recovery times for both destabilizing and stabilizing perturbations were 1 cycle, with the exception of the largest stabilizing perturbation, which was 3 cycles.

-----*Insert Figure 4 about here*-----

*Racket period  $T_r$  is proportional to perturbation magnitude*

Racket adjustments were proportional to the magnitude of the perturbation, as illustrated in Fig. 4a. In the pre-perturbation cycle ( $C_0$ ), the racket period ( $T_r$ ) was flat as expected, but in the first post-perturbation cycle ( $C_1$ ), it was proportional to perturbation magnitude, showing rapid adaptation to small and large perturbations, both negative (stabilizing) and positive (destabilizing). An ANOVA (2 cycles  $\times$  10 magnitudes) on  $T_r$  yielded a main effect of cycle,  $F(1, 15) = 6.99$ ,  $p < 0.05$ ,  $[\eta]^2 = 0.32$ , a main effect of perturbation magnitude,  $F(9, 135) = 112$ ,  $p < 0.05$ ,  $[\eta]^2 = 0.88$ , and most importantly a significant interaction,  $F(9, 135) = 47.9$ ,  $p < 0.0001$ ,  $[\eta]^2 = 0.76$ . A linear regression was performed between  $T_{r1}$  and the ball's perturbed flight time ( $T_{b1}$ ) yielding the equation:  $T_{r1} =$



$0.77 \times T_{bI} + 0.17$ , with  $R^2 = .9977$ . Therefore, the observed value of  $T_{rI}$  is a linear function of ball's perturbed flight time and close to the theoretical value for complete compensation; however, racket period did not fully adapt within one cycle, as shown by the slope of 0.77. The fact that racket adjustments were proportional to perturbation magnitude, rather than to the distance from the stability boundary, is consistent with mixed control but contrary to hybrid control.

*Duration of downswing and upswing.* The timing of the racket adjustment can be analyzed further by decomposing racket period  $T_r$  into the duration of the downswing ( $T_{rdown}$ ) and succeeding upswing ( $T_{rup}$ ) (Fig. 4b and 4c). In the first post-perturbation cycle ( $C_1$ ), the racket adjustment does not occur in the first 420ms downswing ( $T_{rdown1}$ ), but almost entirely by shortening or lengthening the subsequent 320ms upswing ( $T_{rup1}$ ). An ANOVA on  $T_{rdown}$  revealed a main effect of perturbation magnitude,  $F(9,135) = 2.96$ ,  $p < 0.0001$ ,  $[\eta]^2 = .16$ , and a significant magnitude by cycle interaction,  $F(9,135) = 4.93$ ,  $p < 0.01$ ,  $[\eta]^2 = 0.25$ . However, the effect size was small (Fig. 4b), and post hoc Tukey tests failed to find a significant difference between  $C_1$  and  $C_0$  at any perturbation magnitude. A similar ANOVA on  $T_{rup}$  revealed main effects of cycle  $F(1,15) = 46.0$ ,  $p < 0.001$ ,  $[\eta]^2 = .75$ , and perturbation magnitude,  $F(9,135) = 179$ ,  $p < 0.0001$ ,  $[\eta]^2 = .92$ , and a significant interaction,  $F(9,135) = 208$ ,  $p < 0.0001$ ,  $[\eta]^2 = 0.93$ , with a much larger effect size. Thus, following a perturbation at impact, nearly all of the adjustment in racket period occurs 420ms later, during the subsequent upswing.

-----*Insert Figure 5 about here*-----

*Racket period  $T_r$  correlates with the ball's upward flight time  $t_{up}$*

To assess the visual information used to regulate racket timing, the five informational variables in the ball's trajectory were correlated with the three racket cycle variables (Fig. 5). Before the perturbation ( $C_0$ , Fig. 5a), several informational variables naturally covaried with racket period  $T_{r0}$  (mean  $r \sim 0.86$ ). After the perturbation ( $C_1$ , Fig 5a), the correlation of the ball's upward flight time  $t_{up}$  with racket period  $T_{r1}$  remained high (mean  $r = 0.85$ ), and was significantly greater than any other variable ( $p < .05$  or better for all participants, Williams-Hotelling t-tests). In particular, the correlation for ball peak height  $h_{pl}$  was significantly weaker (mean  $r = 0.65$ ), and that for ball launch velocity  $v_{bl}$  was actually negative (mean  $r = -0.27$ ). Contrary to the mirror algorithm, in  $C_0$  the racket period did not correlate with the phase in the downswing at which the ball reached its peak height ( $\phi_{BMax}$ ) (mean  $r = 0.40$ ); the higher correlation with phase in  $C_1$  (mean  $r = 0.68$ ) is a spurious consequence of the ball's perturbed upward flight time.

The influence of the optical variables can be analyzed further by breaking racket period into its downswing and upswing durations (refer to of Fig. 5b,c). Before the perturbation ( $C_0$ ),  $t_{up}$  correlated significantly better with the whole racket period  $T_r$  ( $r = .86$ ) than with either the downswing  $T_{rdown}$  or upswing  $T_{rup}$  ( $p < .05$  or better, Williams-Hotelling t-tests). After the perturbation ( $C_1$ ), the correlation with the upswing  $T_{rup}$  increased to a comparable level ( $r = .81$ ), while the correlation with the whole period  $T_r$  remained high ( $r = .84$ ). This pattern implies that the whole racket cycle is normally modulated by visual information, but participants can rapidly correct the upswing for perturbations late in the racket cycle.

In sum, Exp 1 showed that racket period  $T_r$  is adjusted rapidly in the first cycle after the perturbation, that it varies linearly with perturbation magnitude for stabilizing as well as destabilizing perturbations, and that it is visually regulated by the ball's upward half-period

$t_{up}$ . These results are consistent with a mixed control mode in which the racket oscillation is modulated by the ball's upward flight time on a cycle-by-cycle basis.

## Experiment 2: Visual control of error correction

The purpose of Exp 2 was to answer the outstanding question of how participants correct for errors in bounce height. To isolate the effect of error  $\varepsilon$ , we perturbed both  $g$  and  $v_b$  at impact so as to vary the ball's peak height  $h_p$  with respect to the target, while holding  $t_{up}$  constant. The absolute hypothesis predicts that peak height  $h_p$  (i.e.  $\varepsilon$ ) should be highly correlated with the next racket velocity  $v_r$  required to hit the ball to the target, whereas the relative hypothesis predicts that  $\varepsilon$  should be more strongly correlated with the change in racket velocity from the previous impact  $\Delta v_r$ .

### Methods

#### *Participants and procedure*

Sixteen participants were tested in Exp 2 ( $23.5 \pm 2.6$  years), eight of whom had participated in Exp 1 one year before. The apparatus and procedure were the same as in Exp 1, with one exception: the twenty-four 'perturbation' test trials were 75s long, and ball kinematics were perturbed every 6 cycles on half the trials and every 7 cycles on the other half.

#### *Perturbations*

To dissociate the ball's peak height  $h_p$  from its upward flight duration  $t_{up}$ , we simultaneously perturbed the ball's launch velocity  $v_{b1}$  and  $g_1$  at impact for one full cycle, so

that the total amplitude  $H_1$  of the ball's flight varied while the duration of the flight period  $T_b$  remained unaffected (Fig. 1c). The magnitude of the  $v_b$  perturbation was selected randomly as in Exp 1, so the new ball velocity  $v_b'$  remained within  $\pm 25\%$  of its original value. To keep  $T_b$  unchanged, a new value of  $g$  was applied during the first flight period:  $g' = v_b'/T_b = g(1+x)$ , so that  $t_{up1} = t_{down1}$ . As a consequence, ball amplitude  $H_1$  was modified:  $H_1' = (v_b')^2 / (2g') = H_1(1+x)$ . In sum,  $v_b$ ,  $g$  and  $H$  were perturbed by the same proportion so that the ball's peak height ( $h_{p1}$ ) varied but its upward flight time  $t_{up1}$  was unaffected. At the next impact, the value of  $g$  was reset to the reference value of 9.81, so  $v_{b2}$  was the same as if the ball had dropped from an unperturbed height.

A total of 2209 perturbations were recorded in the 6-cycle trials and 2005 perturbations in the 7-cycle trials. In addition to the previous dependent variables, we also analyzed the racket velocity at impact in  $C_1$  ( $v_{r1}$ ), the change in racket velocity at impact from  $C_0$  to  $C_1$  ( $\Delta v_r$ ), and the amplitude of racket downswing ( $A_{rdown}$ ) and upswing ( $A_{rup}$ ), defined as the difference between successive peak and valley racket positions (Sternad et al. 2001; De Ruyg et al. 2003).

## Results

Compensatory responses to perturbations in bounce height were observed in the first cycle, including proportional adjustments in downswing duration, upswing amplitude, and racket impact velocity; the recovery time for bounce height was under 3 cycles. These results are

again consistent with active regulation of every cycle. Error  $\varepsilon$  from the target had a significantly stronger correlation with the change in racket velocity from the previous impact  $\Delta v_r$ , than the absolute racket velocity  $v_r$ , implying that error correction is achieved by using

bounce error to control the change in impact velocity. We describe these results in detail.-----

-----*Insert Figure 6 about here* -----

### *Recovery time*

As expected by the protocol, negative perturbations produced target undershoot in  $C_1$ , and positive perturbations target overshoot, proportional to perturbation magnitude (Fig. 6). The error in  $C_2$ , of opposite sign to the perturbation, indicates a rapid adjustment on the first post-perturbation impact, with some over-compensation. After  $C_2$ , bounce error decreased over one or two more cycles. To determine the recovery time after negative perturbations (decrease in  $h_{p1}$ ), a two-way repeated measures ANOVA (7 cycles  $\times$  5 magnitudes) on error  $\varepsilon$  yielded main effects of perturbation magnitude,  $F(4, 60) = 4.07$ ,  $p < 0.01$ ,  $[\eta]^2 = 0.21$ , and cycle,  $F(6, 90) = 192$ ,  $p < 0.0001$ ,  $[\eta]^2 = 0.93$ , and a significant interaction,  $F(24, 360) = 35$ ,  $p < 0.0001$ ,  $[\eta]^2 = 0.70$ . For positive perturbations (increase in  $h_{p1}$ ), a similar ANOVA yielded a main effect of cycle,  $F(6, 90) = 145$ ,  $p < 0.0001$ ,  $[\eta]^2 = 0.91$ , and a significant interaction,  $F(24, 360) = 27.7$ ,  $p < 0.0001$ ,  $[\eta]^2 = 0.65$ , but no overall effect of magnitude,  $F(4, 60) = 1.25$ ,  $p = 0.29$ ,  $[\eta]^2 = 0.07$ . Post-hoc Tukey tests found that the error was significantly different from pre-perturbation levels ( $C_0$ ) in cycle  $C_2$  for  $\text{Mag}_{-5}$ ,  $\text{Mag}_{-4}$ ,  $\text{Mag}_{-3}$ ,  $\text{Mag}_{-2}$ ,  $\text{Mag}_3$ ,  $\text{Mag}_4$ ,  $\text{Mag}_5$  ( $p < .001$  or better), and in cycle  $C_3$  (for  $\text{Mag}_{-5}$ ,  $\text{Mag}_{-4}$ ,  $\text{Mag}_4$ ,  $p < .005$  or better). By cycle  $C_4$  the error for even the largest perturbations ( $\text{Mag}_{-5}$ ,  $\text{Mag}_{-4}$ ,  $\text{Mag}_4$ ,  $\text{Mag}_5$ ) was no longer significant. Thus, performance recovered within 3 cycles after both negative and positive perturbations.

-----*Insert Figure 7 about here* -----

*Racket velocity at impact  $v_{r1}$  is proportional to perturbation magnitude*

Racket velocity was adaptively adjusted on the first post-perturbation impact ( $v_{r1}$ ), within one cycle  $C_1$  (Fig. 7a). Specifically, when the ball undershot the target (negative perturbation),  $v_{r1}$  increased, and vice versa. Moreover, the change in impact velocity was proportional to the perturbation magnitude. An ANOVA (2 cycles  $\times$  10 magnitudes) on  $v_r$  yielded a significant interaction,  $F(9,135) = 17.7$ ,  $p < 0.0001$ ,  $[\eta]^2 = 0.54$ , and planned comparisons showed a significant linear trend for  $C_1$ ,  $F(1,15) = 37.9$ ,  $p < 0.0001$ , showing that impact velocity scaled linearly with the perturbation. This rapid, compensatory adjustment to large and small perturbations is again indicative of active error correction on a cycle-by-cycle basis.

#### *Racket amplitude is proportional to the perturbation*

The change in racket velocity was delivered by a corresponding change in racket amplitude, which was much greater on the upswing than the downswing. The amplitudes of racket downswing ( $A_{rdown}$ ) and upswing ( $A_{rup}$ ) are plotted as a function of perturbation magnitude in Fig. 8a and 8b. Following a negative perturbation, the increase in racket velocity at the next impact was delivered by a greater racket amplitude, and vice versa. The ANOVAs (2 cycles  $\times$  10 magnitudes) revealed significant interactions for both the downswing amplitude,  $F(9,135) = 4.65$ ,  $p < 0.0001$ ,  $[\eta]^2 = 0.24$ , and the upswing amplitude,  $F(9,135) = 70.0$ ,  $p < 0.0001$ ,  $[\eta]^2 = 0.84$ , but the magnitude of the effect on  $A_{rup}$  was almost four times that on  $A_{rdown}$ , and proportional to perturbation magnitude.

#### *Racket period $T_r$ responds to perturbations in bounce height*

Despite an unchanged ball flight period during the perturbation in cycle  $C_1$ , racket period in  $C_1$  was smaller than in  $C_0$  for negative perturbations, and larger for positive perturbations, with a linear increase in  $C_1$  racket period (Fig. 7b). This indicates that bounce error elicited

small but reliable adjustments in racket period despite a constant ball flight period. However, compared to Exp 1 the matched perturbations in Exp 2 had a relatively small effect on racket period (Fig. 7b): the largest difference between  $C_0$  and  $C_1$  was only 28ms at Mag<sub>.5</sub> (a 3.7% change in racket period), compared to 82ms for Mag<sub>.5</sub> in Exp. 1 (an 11.1% change). An ANOVA (2 cycles  $\times$  10 magnitudes) on  $T_r$  yielded a main effect of perturbation magnitude,  $F(9,135) = 21.0$ ,  $p < 0.0001$ ,  $[\eta]^2 = 0.58$ , and a significant interaction,  $F(9,135) = 26.9$ ,  $p < 0.0001$ ,  $[\eta]^2 = 0.64$ . Planned comparisons showed a significant linear trend for  $C_1$ ,  $F(1,15) = 131$ ,  $p < 0.0001$ , and Tukey post-hoc tests found that  $C_1$  was significantly different from  $C_0$  at six perturbation magnitudes (Mag<sub>.5</sub>, Mag<sub>.4</sub>, Mag<sub>.3</sub>, Mag<sub>.2</sub>, Mag<sub>.4</sub>, Mag<sub>5</sub>).

*Duration of downswing and upswing.* When racket period is decomposed into the downswing ( $T_{rdown}$ ) and upswing ( $T_{rup}$ ) (Fig. 8c and 8d), it is clear that the change in timing occurs entirely during the  $C_1$  downswing: target undershoot yields a shorter downswing, and target overshoot a longer downswing. The ANOVA (2 cycles  $\times$  10 magnitudes) on  $T_{rdown}$  revealed a significant interaction,  $F(9,135) = 48.5$ ,  $p < 0.01$ ,  $[\eta]^2 = 0.76$ , but there was no interaction for the ANOVA on  $T_{rup}$ ,  $F(9,135) = .97$ , *ns*. Thus, in contrast to the modulation of upswing duration in Exp 1 (Fig. 4c), bounce error elicited a small adjustment in the racket downswing duration.

-----*Insert Figure 8 about here* -----

*Change in racket velocity  $\Delta v_r$  correlates with bounce error  $\varepsilon$*

To assess how error correction is controlled, the informational variables were correlated with the racket variables and the key results are summarized here (Fig. 9). Note that

correlations with bounce error  $\varepsilon$  are equivalent to those with ball peak height  $h_p$ , because they only differ by a constant ( $\varepsilon = h_p - 0.65$ ). Both before ( $C_0$ ) and after the perturbation ( $C_1$ ), the correlation of  $\varepsilon$  with the change in racket velocity  $\Delta v_r$  (mean  $r = -.63, -.60$ ) was significantly stronger than with the absolute racket velocity  $v_r$  (mean  $r = -.32, -.44$ ), for all participants (all  $p < .0001$ , Williams-Hotelling t-tests). The mean regression equation for  $\Delta v_r$  as a function of  $\varepsilon$  was:  $\Delta v_r = 1.57 \times \varepsilon + 0.03$ .

-----*Insert Figure 9 about here*-----

The results of Exp 2 show that active error correction is governed by using bounce error  $\varepsilon$  to regulate the change in racket velocity from the previous impact  $\Delta v_r$ , consistent with the relative hypothesis. Specifically, a negative error ( $\varepsilon_l$ ) elicits a coordinated modulation of racket oscillation within the same cycle ( $C_1$ ): a small decrease in downswing duration ( $T_{rdown1}$ ), preparatory to an increase in upswing amplitude ( $A_{rup1}$ ), to deliver an increase in impact velocity ( $\Delta v_{r1}$ ) relative to the previous cycle; and vice versa for a positive error.

## Discussion

In the present study, we used a rhythmic ball-bouncing task to address three questions about perception and action. First, how are passive stability and active control combined to yield stable, adaptive behavior? Second, what information is used to regulate the period of oscillation to control impact timing? Third, how is the racket velocity at impact regulated to perform error correction? We find that (1) racket adjustments are rapid and proportional to perturbation magnitude, consistent with mixed control; (2) to control timing, the upward half-period ( $t_{up}$ ) of the ball's flight is used to modulate the period of racket oscillation ( $T_r$ ); and (3)



for error correction, error ( $\varepsilon$ ) from the target height is used to regulate the change in racket velocity from the previous impact ( $\Delta v_r$ ), consistent with the relative hypothesis.

The purpose of Exp 1 was to further test the “mixed” control mode, in which participants actively regulate racket motion in order to exploit the passively stability properties of the ball-racket system. Siegler et al. (2010) described four candidate control modes and reported compensatory adjustments in racket period to changes in  $g$  and  $\alpha$  whether they were stabilizing or destabilizing, supporting mixed control. However, only four perturbation magnitudes were tested (small/large; stabilizing/destabilizing) and candidate informational variables in the ball’s trajectory, specifically  $t_{up}$  and peak height  $h_p$ , remained highly correlated. Here we applied graded perturbations in  $t_{up}$  while ball peak height  $h_p$  was kept unchanged in order to test mixed control and dissociate the informational variables. The period of the first racket cycle, particularly the duration of racket upswing, was proportional to perturbation magnitude for both negative and positive perturbations. In other words, racket period was regulated whether the perturbation was large or small, destabilizing or stabilizing. This confirms a mixed control mode in which racket period is adjusted on a cycle-by-cycle basis for all perturbations. On the other hand, it is contrary to hybrid control, in which the response should depend on the distance from the stability boundary and stabilizing or small neutral perturbations should not elicit racket adjustments. Moreover, the greater dissociation of informational variables in Exp 1 compared to Siegler et al. (2010) revealed that the ball’s upward flight time  $t_{up}$  bore a significantly stronger correlation with racket period than did peak height  $h_p$ , launch velocity  $v_b$ , or peak phase  $\phi_{BMax}$ . Thus, racket period is primarily regulated by the ball’s upward half-period. This period controller has two clear advantages: it is dimensionless (the informational variable and control variable are in the same units), and it does not require specific knowledge of  $g$ .

The purpose of Exp 2 was to determine whether error correction is performed by using the ball's peak height ( $h_p$ ) to control racket velocity at impact ( $v_r$ ) or the change in velocity from the previous impact ( $\Delta v_r$ ). The absolute hypothesis (Ronsse et al. 2010) proposes that the ball's peak height is used to compute the exact racket velocity required to correct for bounce error. Wei et al. (2008) had found that the relation between racket velocity and error had a significantly negative slope, with  $R^2$  values near 0.2 ( $r = 0.44$ , slope  $-0.055$ ) for  $\alpha = .5$ . When we perturbed ball peak height in Exp 2, while leaving  $t_{up}$  unchanged, we observed a similarly weak relation with  $v_r$  (mean correlation of  $r = -0.4$ ), but a significantly stronger correlation with  $\Delta v_r$  ( $r = -0.60$ ). Our results thus favor the relative hypothesis that participants use error ( $\varepsilon$ ) to regulate the change in racket velocity from the previous impact ( $\Delta v_r$ ). This is apparently achieved by modulating the duration of racket downswing ( $T_{rdown}$ ) and the amplitude of racket upswing ( $A_{rup}$ ) relative to the previous cycle.

Together with previous findings, the present results give us a comprehensive picture of this model perception-action system. The most important conclusion is that such systems exploit passive dynamics to simplify the task in combination with active control. Behavior is organized around dynamic stabilities, but uses information to maintain adaptive flexibility. In the present case, the actor adopts a mixed control mode in which information in the ball's trajectory is used to actively stabilize behavior on a cycle-by-cycle basis, in order to keep the system within or near the passively stable region. We now understand precisely how these adjustments are visually controlled: the period of racket oscillation is modulated by the half-period of the ball's upward flight, and the change in racket velocity from the previous impact is governed by the error to the target. Active control provides rapid adaptive responses to changes in environmental conditions, while staying near the passive regime serves to minimize the adjustments needed to maintain bouncing. Mixed control thus offers a general solution for biological systems interacting with the physical world.

## Reference List

Bühler M, Koditschek DE, Kindlmann PJ (1994) Planning and control of robotic juggling and catching tasks. *International Journal of Robotics Research* 13:101-118

Collins S, Ruina A, Tedrake R, Wisse M (2005) Efficient bipedal robots based on passive-dynamic walkers. *Science* 307:1082-1085

de Rugy A, Wei K, Muller H, Sternad D (2003) Actively tracking 'passive' stability in a ball bouncing task. *Brain Res* 982:64-78

Dijkstra TMH, Katsumata H, de Rugy A, Sternad D (2004) The dialogue between data and model: passive stability and relaxation behavior in a ball-bouncing task. *Nonlinear Studies* 11:319-344

Kulchenko P, Todorov E (2011) Fire-exit model predictive control of fast discontinuous dynamics: Applications to ball bouncing. *IEEE International Conference on Robotics and Automation*, 2144-2151. doi: 10.1109/ICRA.2011.5980196

Kuo AD (2007) The six determinants of gait and the inverted pendulum analogy: A dynamic walking perspective. *Hum Mov Sci* 26:617-656

Morice AH, Siegler IA, Bardy BG (2008) Action-perception patterns in virtual ball bouncing: combating system latency and tracking functional validity. *J Neurosci Methods* 169:255-266

Morice AH, Siegler IA, Bardy BG, Warren WH (2007) Learning new perception-action solutions in virtual ball bouncing. *Exp Brain Res* 181:249-265

Ronsse R, Sternad D (2010) Bouncing between model and data: stability, passivity, and optimality in hybrid dynamics. *J Mot Behav* 42:389-399

Ronsse R, Wei K, Sternad D (2010) Optimal control of a hybrid rhythmic-discrete task: the bouncing ball revisited. *J Neurophysiol* 103:2482-2493

Schaal S, Atkeson CG, Sternad D (1996) One-Handed Juggling: A Dynamical Approach to a Rhythmic Movement Task. *J Mot Behav* 28:165-183

Siegler IA, Bardy BG, Warren WH (2010) Passive vs. active control of rhythmic ball bouncing: the role of visual information. *J Exp Psychol Hum Percept Perform* 36:729-750

Sternad D, Duarte M, Katsumata H, Schaal S (2000) Dynamics of a bouncing ball in human performance. *Physical Review E* 63: 011902.1-011902.8.

Sternad D, Duarte M, Katsumata H, Schaal S (2001) Bouncing a ball: tuning into dynamic stability. *J Exp Psychol Hum Percept Perform* 27:1163-1184

Todorov E, Jordan MI (2002) Optimal feedback control as a theory of motor coordination. *Nat Neurosci* 5:1226-1235

Turvey MT (1990) The challenge of a physical account of action: A personal view. In: Whiting HTA, Meijer OG, van Wieringen PCW (eds) *The natural-physical approach to movement control*. VU University Press, Amsterdam, pp 57-93

Warren WH (1988) Action modes and laws of control for the visual guidance of action. In: Meijer O, Roth K (eds) *Complex movement behavior: the motor-action controversy*. North Holland, Amsterdam, pp 339-380

Warren WH (2006) The dynamics of perception and action. *Psychol Rev* 113:358-389

Wei K, Dijkstra TM, Sternad D (2007) Passive stability and active control in a rhythmic task. J Neurophysiol 98:2633-2646

Wei K, Dijkstra TM, Sternad D (2008) Stability and variability: indicators for passive stability and active control in a rhythmic task. J Neurophysiol 99:3027-3041

## Figure captions

**Fig. 1 a.** Definition of racket and ball variables. **b.** Schematic of perturbations in ball kinematics in Exp 1. Half-period of the ball ( $t_{up}$ ) is perturbed while ball amplitude (H) remains unchanged. **c.** Schematic of perturbations in Exp 2. Ball amplitude (H) is perturbed while ball period ( $T_b$ ) and half-period ( $t_{up}$ ) remain unchanged

**Fig. 2. Experimental set-up (reproduced from Siegler et al. (2010))**

**Fig. 3** Racket acceleration at impact (mean  $\pm$  Standard Error) in cycles  $C_0$  and  $C_1$  as a function of perturbation magnitude in Exp 1.

**Fig. 4** Duration variables in cycles  $C_0$  and  $C_1$  as a function of perturbation magnitude in Exp 1. **a.** Racket cycle period  $T_r$  (mean  $\pm$  S.E). Graph also displays the theoretical duration of the ball trajectory if ball is hit in  $C_1$  at the same racket vertical position as in  $C_0$ . **b.** Downswing duration  $T_{rdown}$  (mean  $\pm$  S.E). **c.** Upswing duration  $T_{rup}$  (mean  $\pm$  S.E)

**Fig. 5.** For the pre-perturbation ( $C_0$ ) and post-perturbation ( $C_1$ ) cycle, correlation coefficients between informational variables and (A) racket period, (B) duration of racket downswing, and (C) duration of racket upswing. ( $t_{up}$ =duration of ball upward flight,  $t_{down}$ =duration of ball downward flight,  $h_p$ =peak height of ball,  $v_b$ =ball launch velocity,  $\phi_{BMax}$ =phase in racket cycle of peak ball height)

**Fig. 6** Error to target  $\mathcal{E}$  (mean  $\pm$  S.E) from  $C_0$  to  $C_6$ , for negative (a) and positive (b) perturbation magnitudes in Exp 2

**Fig. 7 a.** Racket velocity at impact  $V_r$  (mean  $\pm$  s.e) in cycle  $C_0$  and  $C_1$  as a function of perturbation magnitude (Exp 2)**b.** Racket cycle period  $T_r$  (mean  $\pm$  S.E) of  $C_0$  and  $C_1$  as a function of perturbation magnitude (Exp 2).

**Fig 8.** Characterization of racket downswing and upswing in cycles  $C_0$  and  $C_1$  as a function of perturbation magnitude (Exp 2). **a.** Downswing amplitude  $A_{rdown}$  (mean  $\pm$  S.E). **b.** Upswing amplitude  $A_{rup}$  (mean  $\pm$  S.E).**c.** Downswing duration  $T_{rdown}$  (mean  $\pm$  S.E). **d.** Upswing duration  $T_{rup}$  (mean  $\pm$  S.E).

**Fig. 9.** For the pre-perturbation ( $C_0$ ) and post-perturbation ( $C_1$ ) cycle, correlation coefficients between error to the target ( $\mathcal{E}$ ) and racket velocity ( $\Delta V_r$ ,  $V_r$ ).

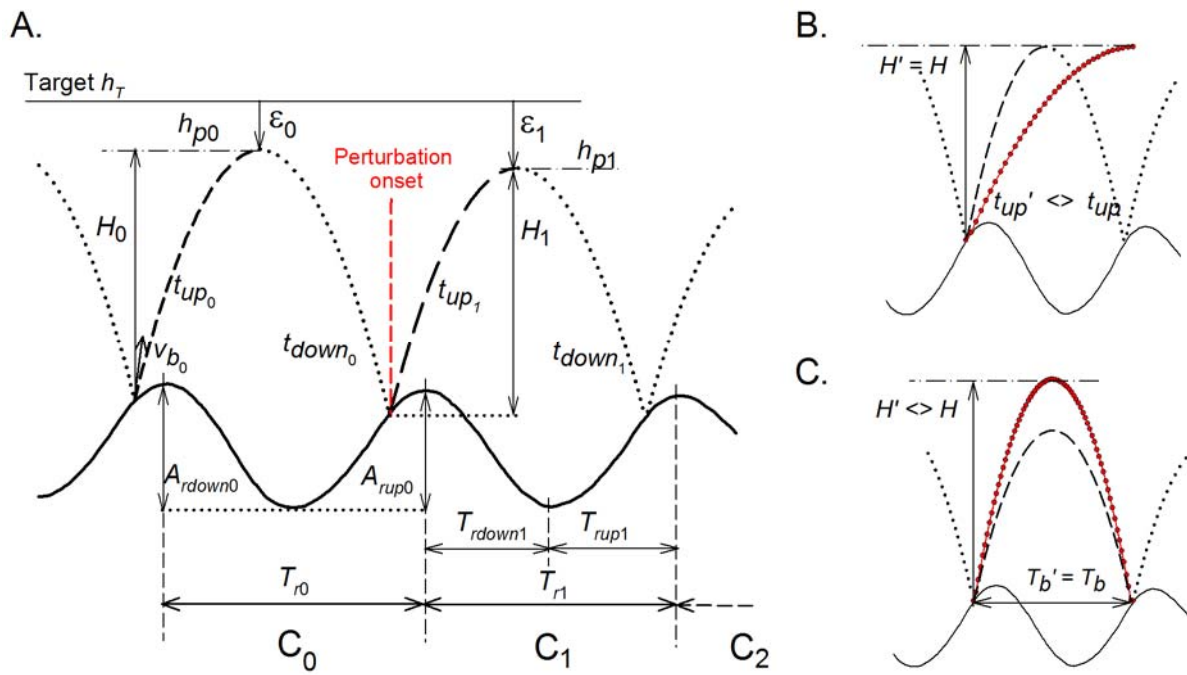


Figure 1

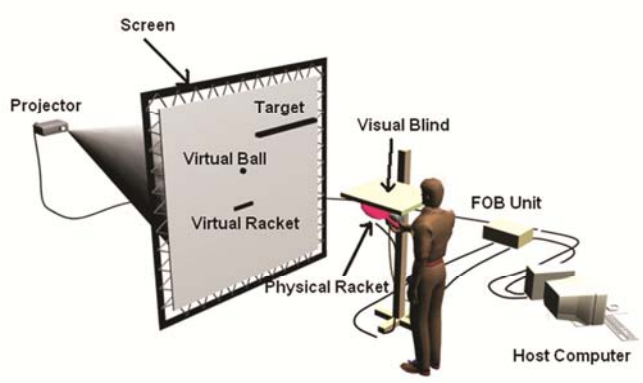


Figure 2

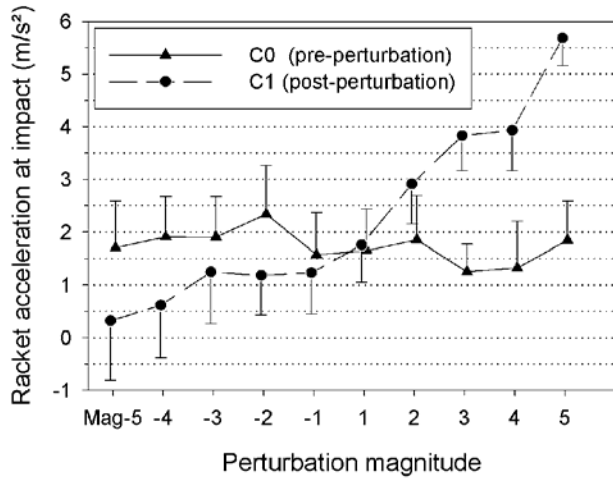


Figure 3



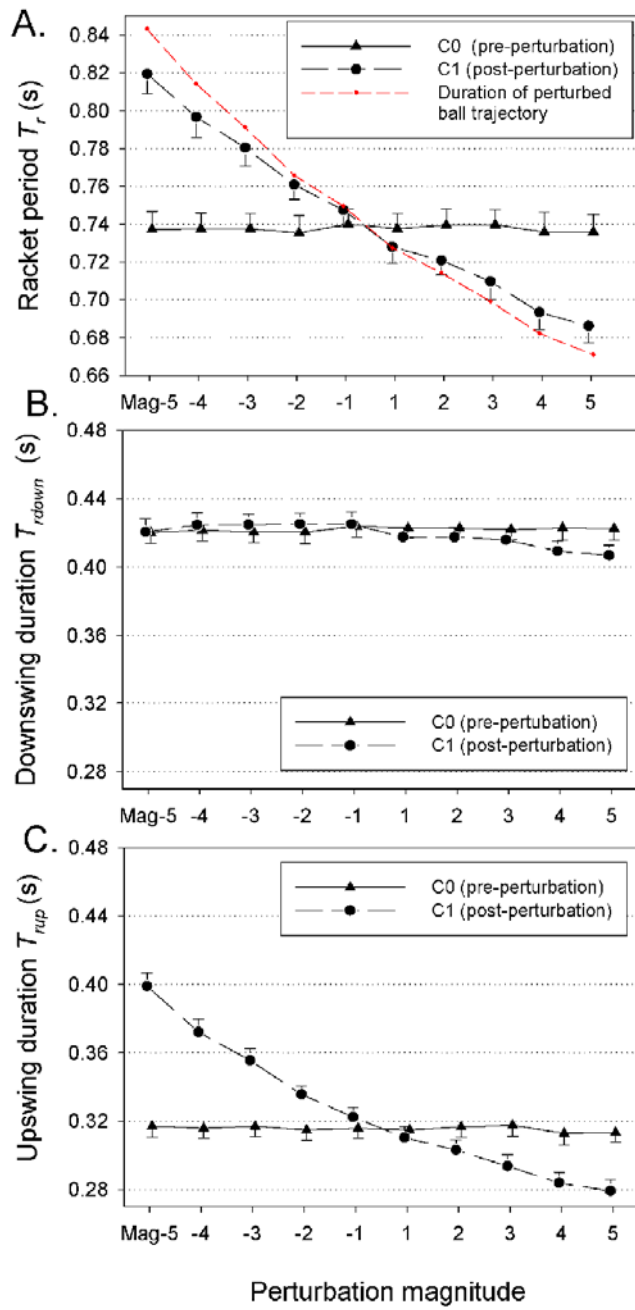


Figure 4

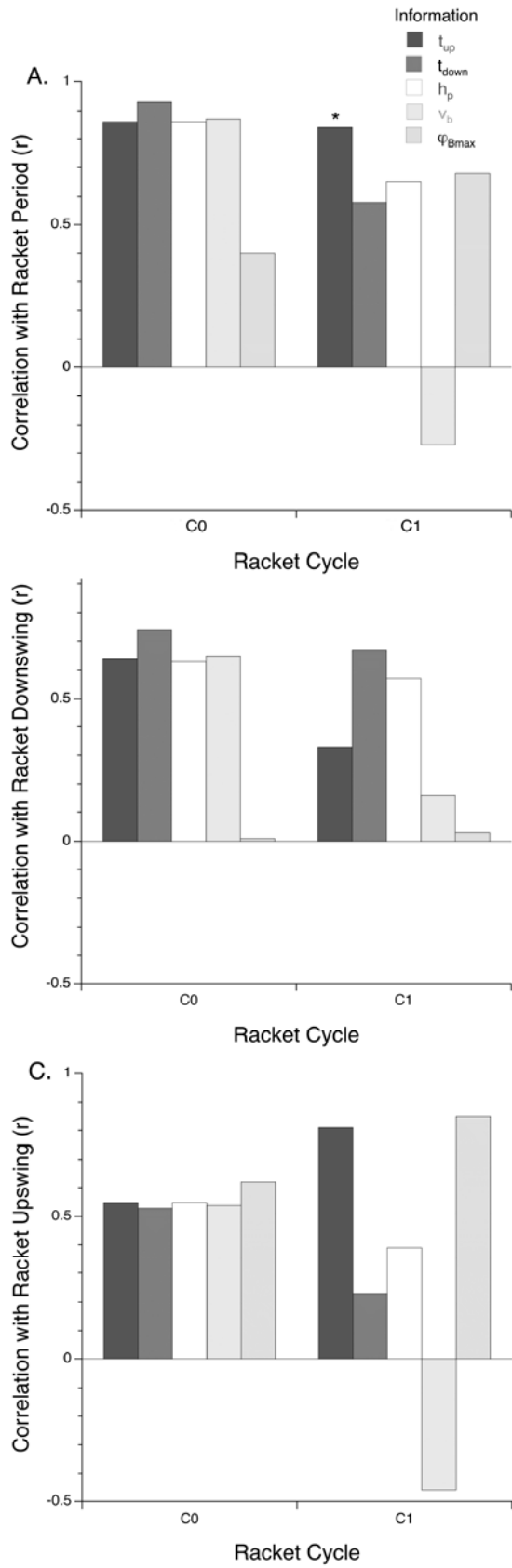


Figure 5

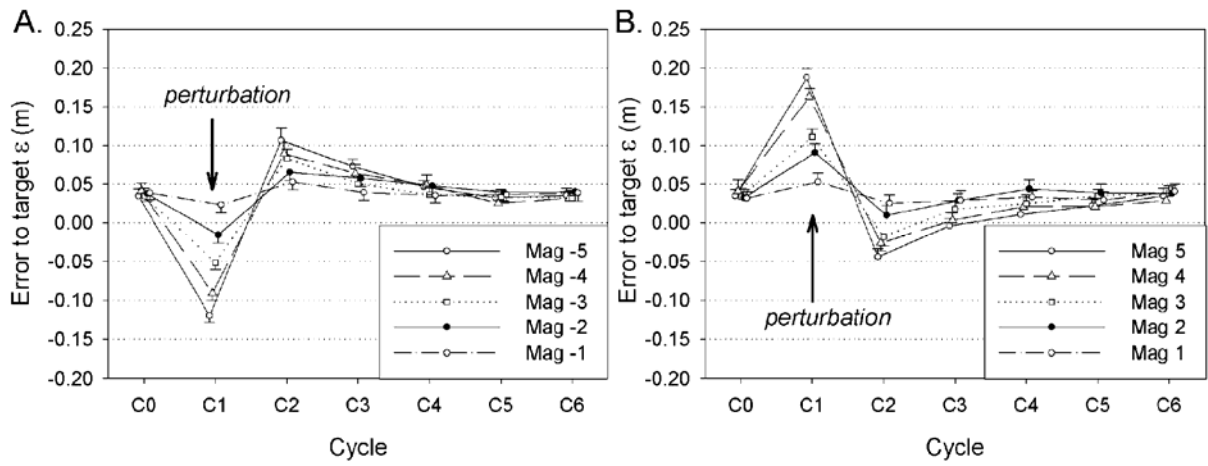


Figure 6

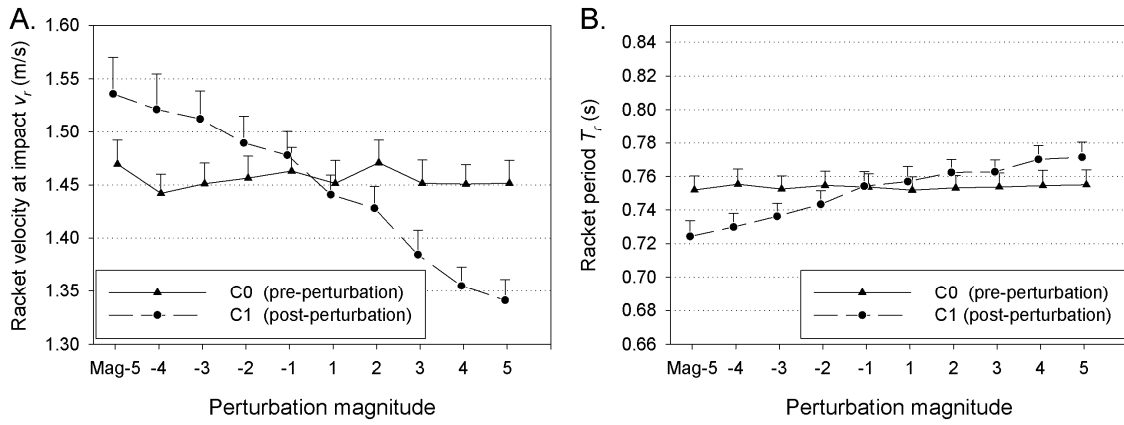


Figure 7

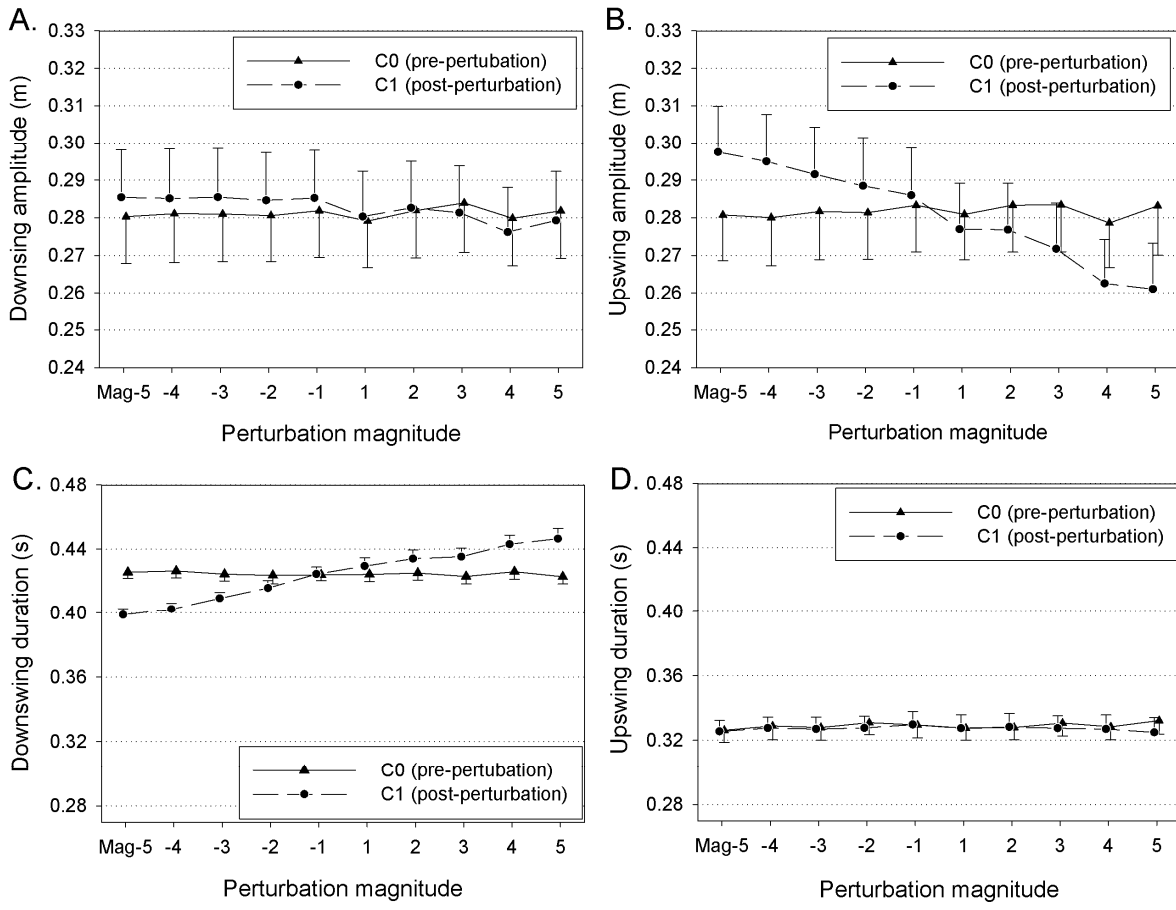


Figure 8

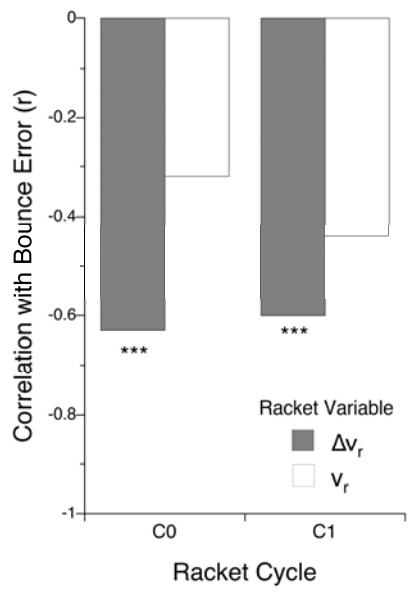


Figure 9