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Passive vs. Active Control of Rhythmic Ball Bouncing: The Role of Visual Information

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The simple task of bouncing a ball on a racket offers a model system for studying how human actors exploit the physics and information of the environment to control their behavior. Previous work shows that people take advantage of a passively stable solution for ball bouncing but can also use perceptual information to actively stabilize bouncing. In this article, we investigate (a) active and passive contributions to the control of bouncing, (b) the visual information in the ball's trajectory, and (c) how it modulates the parameters of racket oscillation. We used a virtual ball bouncing apparatus to manipulate the coefficient of restitution α and gravitational acceleration g during steady-state bouncing (Experiment 1) and sudden transitions (Experiment 2) to dissociate informational variables. The results support a form of mixed control, based on the half-period of the ball's trajectory, in which racket oscillation is actively regulated on every cycle in order to keep the system in or near the passively stable region. The mixed control mode may be a general strategy for integrating passive stability with active stabilization in perception–action systems.

Keywords: perception and action, visual control, rhythmic movement, dynamical systems

Adaptive behavior, by definition, requires the spatiotemporal coordination of one's actions with the surrounding environment. Accounting for the organization of adaptive behavior thus depends on understanding the dynamics of the interaction between agent and environment (Warren, 2006). A critical issue is the degree to which human actors exploit environmental constraints, including physical properties and informational variables, in order to achieve stable patterns of behavior in a given task. To the extent that they do so, responsibility for the organization in behavior cannot simply be attributed to internal neural structure, but must be distributed across an embodied agent and its environment (Gibson, 1979).

The task of bouncing a ball on a racket offers a deceptively simple model system with which to investigate these behavioral dynamics. Rhythmically hitting a ball to a constant height implicates the entire cycle of perception and action: when the racket applies a force to the ball at impact, this alters the state of the environment and generates multisensory information about the ball's trajectory, which can reciprocally be used to regulate the racket cycle. The central question is precisely how the actor exploits the physical and informational constraints of the ball–racket system to stabilize rhythmic bouncing.

Schaal, Atkeson, and Sternad (1996) originally showed that if the ball is hit at a particular point in a racket's harmonic cycle, bouncing is *passively stable*, that is, will continue to a constant height indefinitely despite small perturbations, without active perceptual control. The evidence indicates that participants indeed prefer the passively stable regime (Sternad, Duarte, Katsumata, & Schaal, 2001), and thus appear to exploit this physical stability property. However, recent results also show that participants *actively stabilize* bouncing under some conditions (de Rugy, Wei, Muller, & Sternad, 2003; Morice, Siegler, Bardy, & Warren, 2007), implying that they also take advantage of perceptual information to control the racket oscillation. In the present study we use a virtual bouncing apparatus to investigate three issues: first, the contributions of active and passive control to the stabilization of bouncing; second, the visual information that is used for this control; and third, the parameters of racket oscillation that are modulated by such information.

Dynamics of Ball Bouncing

The dynamics of bouncing a ball on a racket in one (vertical) dimension was analyzed by Schaal et al. (1996) and Dijkstra, Katsumata, de Rugy, and Sternad (2004). Assuming that racket motion is harmonic (sinusoidal), the *bouncing ball map* predicts the state variables of racket phase ϕ_r at impact and ball launch velocity v_b after impact, for given parameter values of the gravitational constant g, coefficient of restitution α, racket period T_r, and racket amplitude A_r. The coefficient of restitution represents the elasticity of the ball-racket system (i.e. the "bounciness" of the

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ball with a constant racket). Analysis of the bouncing ball map demonstrated the existence of a passive stability regime: If impact occurs during the last quarter of the racket cycle, when the racket's upward motion has a positive velocity but is decelerating, then following small perturbations of the ball or racket the system will relax back to a stable *period-1 attractor*, with constant values of v_b ϕ_r, and bounce height. The bouncing ball system is thus self-stabilizing, such that small errors will die away without active error correction.

Specifically, the ball-racket system is passively stable if racket acceleration at impact (a_r) remains in the negative range

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

For example, with $\alpha = 0.5$ and $g = 9.8$ m/s^2, racket acceleration must be between -10.9 and 0 m/s^2 for passive stability, and analysis revealed a narrower region of maximal stability between –5 and –2 m/s^2. Intuitively, self-stabilization occurs because an upward perturbation of the ball will delay impact with the decelerating racket, so the racket will have a lower impact velocity and hit the ball to a lower height, yielding an earlier impact in the next cycle. Over multiple cycles, this compensates for the upward perturbation; and vice versa for a downward perturbation. Thus, exploiting passive stability obviates the need for active error correction of small perturbations.

Passive or Active Stabilization?

However, the existence of a passively stable regime does not rule out a contribution of active perceptual control. Perceptual information may be used to identify the passive regime during learning, to initialize the system in the passive region at the onset of bouncing, or to maintain ongoing bouncing. The first aim of the present study was to determine the mode of control used to maintain bouncing, specifically how it combines active and passive stabilization.

At one extreme is (a) the pure *passive control* hypothesis, which argues that bouncing is maintained through passive stabilization alone in an open-loop fashion, without relying on perceptual information. At the other extreme is (b) the pure *active control* hypothesis, that perceptual information is used to actively stabilize bouncing on every cycle in a closed-loop fashion, without regard to passive stability. One example is the "mirror algorithm" in which racket velocity symmetrically mirrors ball velocity, yielding bouncing outside the passively stable range, with positive impact accelerations (Bühler, Koditschek, & Kindlmann, 1994). An intermediate hypothesis is what we will call (c) *hybrid control*, in which small perturbations are passively stabilized while large perturbations outside the passive range are actively stabilized. This implies a threshold at the stability boundary where perceptual control is initiated, based on the magnitude of the perturbation. Finally, (d) 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 adjustment and increasing stability.

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

However, subsequent reports found that bouncing could also be sustained in the unstable region, with positive impact accelerations, implicating a form of active control (Siegler, Mantel, Warren, & Bardy, 2003; Morice et al., 2007). To probe this possibility, de Rugy et al. (2003) perturbed the coefficient of restitution α at single impacts during ongoing bouncing (equivalent to perturbing the launch velocity), destabilizing the system on a majority of trials. They observed that participants rapidly compensated for large perturbations by adjusting the period of racket oscillation, so that impact acceleration and phase returned to the passively stable range within two to three cycles. These results are suggestive of hybrid control, in which perturbations beyond the passively stable range are actively corrected.

While this article was in preparation, Wei, Dijkstra, and Sternad (2007) reported a study that manipulated both large and small perturbations in α. They again found relaxation times of only two to three cycles, much more rapid than predicted by passive stabilization (Dijsktra et al., 2004). Moreover, they observed that racket adjustments were proportional to the magnitude of perturbation within as well as beyond the stable region, consistent with active control. But there were also traces of passive stability, for bouncing generally returned to the negative acceleration range, larger perturbations required longer relaxation times, and decreases in α yielded longer relaxation times than increases in α. They interpreted these results as evidence for a "blend" of active and passive stabilization.

More recently, Wei, Dijkstra, and Sternad (2008) looked for the presence of active control components when the task was performed at steady state in different stability conditions (by varying α from 0.3 to 0.9). Wei et al (2008) interpreted significant differences between the autocovariance functions of the predictions of the passive stability model and the data as differences in the time needed to compensate for errors and therefore as the presence of active control components. Yet, significant differences were only exhibited for high values of α ($\alpha \geq 0.6$), which lead to very bouncy balls and the most unstable conditions. This main analysis did not show that active control was present at lower values of α. Wei et al. (2008) also performed regressions between perceptual variables and action variables. As they observed that the slopes were more negative when calculated on the experimental data than on the model data, for all participants and all α values, Wei et al. (2008) concluded that participants did use active error compensation. However, these two analyses appear to be inconsistent for the more stable conditions, and further studies are needed to gain insight into this important question.

Thus, taken together, the existing pattern of data is most consistent with the mixed control hypothesis, by which bouncing is actively controlled on every cycle to keep the system within or near the passively stable region. Here we test the hypotheses using a converging approach, by manipulating g as well as α and analyzing the dependency of racket adjustments on the ball's trajectory.

Information for Active Control

These findings implicate a role for perceptual information in the active control of bouncing. The second aim of the present study was thus to determine the optical variables of the ball's trajectory that are used for active stabilization. A number of variables are potentially informative about the timing of the upcoming impact, and thus could be used to regulate the period and phase of racket oscillation. They include (a) visual information in the ball's trajectory; (b) haptic information about the time and force of the current impact; (c) acoustic information about the time, and possibly the force, of the current impact; and (d) combinations of the above variables.

In the first investigation of informational variables, Sternad et al. (2001) withdrew either visual or haptic information once the participant had achieved stable bouncing on each trial. Surprisingly, with only haptic (and acoustic) information available, bouncing could be maintained at the optimal mean negative impact acceleration, although its variability increased significantly compared to a full-information control. This demonstrates that haptic (and acoustic) information is sufficient to sustain bouncing in the passively stable region, but it also implies a stabilizing role for vision. Conversely, bouncing could also be maintained with only visual (and acoustic) information available, although the mean impact acceleration was close to zero (marginally stable), and its variability again increased. This result implies that haptic information also plays a stabilizing role and more accurately specifies the maximally stable region. Finally, Morice et al. (2007) found that bouncing can be maintained outside the passively stable region with vision alone, confirming that visual information is sufficient for active stabilization.

We can formalize the information these variables offer to specify the time-to-impact (refer to Figure 1). Assume that ball mass m_b, coefficient of restitution α, and gravitational acceleration g are constant under given conditions, and that contact with the racket occurs at a constant height (h_c). To stabilize bouncing, the agent must hit the returning ball at a particular phase in the racket cycle

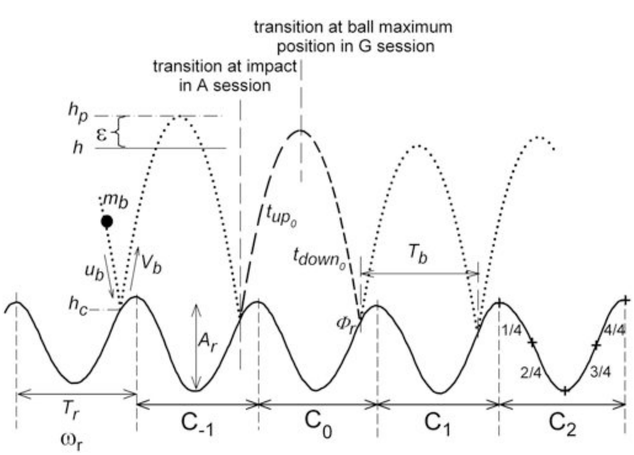

Figure 1. Definition of variables for racket motion (solid line, subscript r) and ball trajectory (broken lines, subscript b). C_0 labels the racket cycle containing a key event; in Experiment 2, g transitions occur at the ball peak during C_0, and α transitions occur at impact just prior to C_0. t_{up0} *and* t_{down0} refer to upward and downward ball flight (dashed line) during C_0. Racket cycles can be subclassified into four quarter-cycles, corresponding to phases of acceleration and deceleration.

(ϕ_r) when racket acceleration is negative. Hence, useful temporal information would specify the period of the ball's flight from impact to impact (T_b), or the time from the peak of flight until the ball returns to the contact height (t_{down}).

First, consider haptic information (the derivation appears in Appendix A). The ball's ith flight period T_i, relative to the previous period T_{i-1}, is proportional to the force F_i and duration Δt_i of contact,

$$T_i = \alpha T_{i-1} + \frac{2F_i \Delta t_i}{g m_b} \tag{2}$$

where $F\Delta t = I$ is the impulse at impact. Thus, for a given ball the change in the upcoming flight period is specified by haptic information about the impact impulse. This information could be used to adjust racket period to match flight period and maintain a constant impact phase. To determine whether this solution is stable, the haptic system would also have to determine the acceleration and phase at the moment of impact from proprioception about arm motion. Note, however, that Eq. 2 depends on α and g, and thus the information would have to be rescaled to new conditions over multiple bounces. In principle, haptic information could thus account for the ability to maintain stable bouncing after vision is withdrawn (Sternad et al., 2001), although it is insufficient to initialize bouncing with an unknown ball or to rapidly correct for ball perturbations during flight.

Second, acoustic variables specify the moment of impact, and sound intensity may provide information about the force of impact. Thus, analogous to Eq. 2, acoustic information could also be used to determine the change in flight period and maintain stable bouncing, although not to initialize bouncing or rapidly correct for perturbations during flight.

Third, there are a number of optical variables from the ball's trajectory that could be used to determine the time-to-impact and to correct for perturbations during flight. We identified four candidate hypotheses, most of which depend on g (derivations appear in Appendix B).

(i) Launch velocity. Assuming that g is known, the ball's flight time (period T_b) is specified by its launch velocity v_b. Half of this value corresponds to the downward flight time from the peak to the contact height (t_{down}):

$$t_{down} = \frac{v_b}{g} \quad \text{or} \quad T_b = \frac{2v_b}{g} \tag{3}$$

(ii) Peak height. Given that g is known, the downward flight time is determined by its peak height h_p. The flight period is twice this value:

$$t_{down} = \sqrt{\frac{2h_p}{g}} \quad \text{or} \quad T_b = 2\sqrt{\frac{2h_p}{g}} \tag{4}$$

Note that the visually perceived height may also depend on the perceived distance of the ball, or on other aspects of the visual context. When astronauts in zero-g conditions were asked to catch a falling ball travelling at a constant velocity, McIntyre, Zago, Berthoz, and Lacquaniti (2001) reported that they were adapted to earth's gravitational acceleration ($g = 9.81$ m/s^2), and hence responded too early. This suggests that participants could use height information to control bouncing if g is implicitly known.

(iii) Half-period. The duration of the downward half-period of the ball's flight from peak to contact (t_{down}) is equal to that of the upward half-period from contact to peak (t_{up}). The total flight period is thus twice this value:

$$t_{down} = t_{up} \quad \text{or} \quad T_b = 2t_{up}. \tag{5}$$

It is important that this relationship does not depend on g, as long it remains constant during the ball's flight. This gives us a means of dissociating the half-period hypothesis from the other informational variables.

(iv) Tau-gap. During the ball's descent, the movement of the racket could be guided by the tau of the motion-gap, that is, the rate of closure of the spatial gap between the ball and the racket positions. The tau-gap τ_c is the first-order time-to-closure of the motion-gap, i.e., the current size of the motion-gap x divided by its current rate of closure $\dot{x}$ (Lee, 1976; Bootsma & Oudejans, 1993):

$$\tau_c = x/\dot{x}. \tag{6}$$

Unless g is additionally taken into account, this variable overestimates the actual time-to-closure, but it converges as the ball approaches the contact height.

In the present experiments, we sought to determine the effective visual information in the ball's trajectory. Three of the ball variables described above depend upon a known g, whereas half-period information does not: the duration of the downward half-period of the ball's trajectory is the same as that of the upward half-period regardless of g. We thus dissociated these variables by changing g to a new constant value at the peak of the ball's trajectory, which allowed us to test several hypotheses. First, if participants rely on peak height (h_p), launch velocity (v_b), or tau-gap (τ_c), they would have to relearn a new implicit value of g over a number of bounces, and should thus exhibit predictable errors in racket timing following a transition in g. McIntyre et al.'s (2001) observation that astronauts failed to adapt to zero-g conditions in 90 trials of ball catching implies that g may not be quickly relearned. Second, if participants rely on the duration of the upward half-period (t_{up}), they should rapidly adapt racket motion to the new value of g, possibly within one cycle. Third, because a sudden change in α at impact does not alter the informativeness of any of these variables, it should elicit rapid adaptation regardless of the information used. Finally, pure passive control should produce no racket adjustments after g or α transitions, and error should increase on subsequent bounces. Correlations between ball variables and racket variables thus allow us to make inferences about the effective visual information.

The Racket Oscillator

The third aim of this study was to determine the parameters of racket motion that are modulated during active control, in order to characterize the racket oscillator. The bouncing task involves rhythmic movement of the forearm about the elbow, which can be modeled as a nonlinear oscillator defined over neuromuscular and biomechanical components. As a first approximation, racket oscillation can be described by three variables: period, amplitude, and phase, various combinations of which can yield a given racket velocity at impact. To maintain bouncing to a constant target height h, the required racket velocity at impact (v_r) is strongly constrained by the environmental parameters α, g, and h, as follows:

$$v_r = \frac{\alpha - 1}{\alpha + 1}\sqrt{2gh} \tag{7}$$

(Note that impact velocity is not completely determined by environmental conditions, because the racket height at impact and the bouncing error to the target may also vary.) For sustained accurate bouncing, we can identify the following constraints on the racket variables. First, the racket period should approximate the ball's flight period, which is strongly dependent on g and h (by Equation 4). Second, the racket phase at impact may theoretically vary, but to satisfy passive stability it should be constrained to the upward decelerating quarter-cycle of racket motion. Third, given a period and phase, racket amplitude should be adjusted to produce the impact velocity demanded by α, g, and h (Equation 7). Note, however, that the relation among these three racket variables may vary as long as they generate the required impact velocity.

A dynamical modeling strategy was pioneered by Kay, Kelso, Saltzman, and Schöner (1987) in a study of wrist oscillation. As the pacing frequency was increased using a metronome, they observed a monotonic decrease in the amplitude of wrist movement and a monotonic increase in peak velocity. The minimal model that could account for these data was a hybrid limit cycle oscillator with nonlinear damping. The damping component included a Rayleigh term that depended on position and captured the amplitude effect, and a Van der Pol term that depended on velocity and captured the peak velocity effect. It is important that both these effects of frequency were reproduced by changing a single control parameter, the oscillator's stiffness coefficient.

Beek, Rikkert, and van Wieringen (1996) sought to generalize the model to rhythmic forearm movements about the elbow. As pacing frequency increased, they also observed that amplitude decreased in all participants, whereas peak velocity increased in only a minority of participants and decreased in the majority. To account for the latter group, Beek et al. (1996) proposed a revised Rayleigh term that depends on frequency as well as position. A key question for models of bouncing is thus whether racket amplitude and period are related, as observed by Kay et al. (1987) and Beek et al. (1996), or can be controlled independently.

Such models suggest that rhythmic movements might be perceptually controlled by coupling informational variables to oscillator control variables (Warren, 2006); the control variables may either be state variables (Schöner, 1991) or parameters (Bingham, 2004; Kay & Warren, 2001). In the case of bouncing, racket period might be controlled by using visual information about the ball's flight period to modulate a stiffness parameter, racket phase by additional information about the previous impact phase, and racket amplitude by visual information about the error to the target. For instance, de Rugy et al. (2003) modeled racket motion using a neural half-center oscillator and compensated for perturbations by using the ball's launch velocity, which specifies it's flight period (Eq. 3), to reset the oscillator period. This served to maintain the desired impact phase and restore the period of bouncing over the next several cycles. However, an empirical control model will depend on both the form of the oscillator and the information actually used to regulate it. By investigating the effective visual information and how it modulates the racket oscillator, we seek to constrain the relevant class of models.

We studied the modulation of racket parameters by varying the environmental conditions α and *g* and testing the following predictions, under the constraint of bouncing to a constant target height. First, with an increase in *g* one would expect a compensatory decrease in racket period, possibly accompanied by adjustments in amplitude and/or phase to produce the required impact velocity. Second, with an increase in α, one would expect a compensatory decrease in racket amplitude to produce the required velocity, but no shift in racket period. An observed independence (or dependence) of racket period and amplitude would place constraints on the relevant class of model oscillators. Finally, correlations between ball variables and racket variables should allow us to infer the coupling of visual information to control parameters.

We conducted two experiments to investigate the mode of control during bouncing, the information used, and how it modulated the racket oscillator. In Experiment 1, we examined steady-state bouncing under various environmental conditions with constant values of *g* and α. In Experiment 2, we examined adaptation of racket oscillation to sudden changes in *g* or α.

General Methods

Participants

Thirteen participants (27.8 ± 5.3 years) were tested in the two experiments presented here. They were informed about the experimental procedure and signed a consent form. Participants had previously taken part in one or two ball-bouncing experiments, and thus had learned how to produce stable bouncing (Sternad et al., 2001).

Apparatus

The virtual ball-bouncing setup was previously described in Morice et al. (2007). Briefly, participants manipulated a table tennis racket (the physical racket) to control the motion of a virtual racket on screen, in order to bounce a virtual ball in the vertical dimension only (see Figure 2). They stood in front of a large rear-projection screen (2.70 m wide × 1.25 m high) at a distance of 1.5 m and held the table tennis racket in their preferred hand. A sheet of cardboard at neck level prevented them from seeing the racket. Racket position was measured by an electromagnetic sensor (Flock of Bird, Model 6DFOB, Ascension Technologies) attached to its underside, with a sampling rate of 120 Hz. The vertical position signal was used to compute the vertical position of the virtual racket, which was displayed as a horizontal bar (20 × 2.5 cm) on the screen using an LCD projector (50 Hz). The position of a virtual ball (diameter = 0.04 m) and its interaction with the virtual racket were also computed and displayed on the screen. A sound was played at contact between the virtual racket and ball. A predictive filter algorithm (8.3-ms polynomial predictive regression) was implemented to reduce the delay in updating the position of the virtual racket. The end-to-end visual latency of the display was measured to be 29.78 ms ± 1.07 ms (see Morice, Siegler, & Bardy, 2008, for details). Environmental parameters could be changed during ongoing bouncing, including the coefficient of restitution α, which affects the change in ball velocity at impact, and virtual gravity *g*, which determines the ball's acceleration.

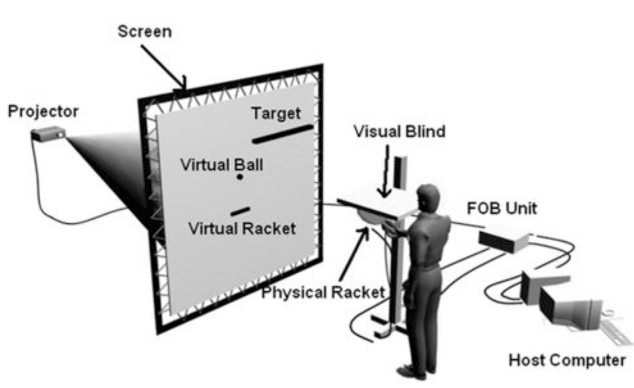

Figure 2. The virtual ball bouncing apparatus. FOB = Flock of Bird, Model 6DFOB, Ascension Technologies.

Procedure

All participants took part in both experiments, with Experiment 1 preceding Experiment 2 (see next section). Each experiment consisted of two sessions presented in a randomized order: in Session G the gravitational constant *g* was manipulated, and in Session A the coefficient of restitution α was manipulated. Target height *h* was always 0.5 m. The target height was defined 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°. Mean impact heights were within 2 cm of this zero position, with SDs less than 5 cm (see Table 1).

In each Session, there were five environment conditions (Cd1, Cd2, Cd3, Cd4, Cd5) with combinations of *g* and α chosen so that the required impact velocities would be close to 0.90, 1.00, 1.10, 1.20 and 1.30 m/s, respectively (by Equation 7). The *reference condition* (Cd3) was identical in both Sessions, with $g = 9.81$ m/s^2 and α = 0.48. In Session G, *g* was varied (6.56, 8.10, 9.81, 11.66, 13.69 m/s^2, in each condition respectively) while α was kept constant at the reference value (α = 0.48). These values of *g* were associated with different required racket periods according to Equation 4 (0.78, 0.70, 0.64, 0.59, 0.54 s, respectively). In Session A, α was varied (0.55, 0.52, 0.48, 0.45, 0.41, in each condition respectively) while *g* was kept constant at the reference value ($g =$ 9.81 m/s^2). A lower coefficient of restitution required a higher racket velocity at impact, but no change in racket period (predicted value of 0.64 s). In Experiment 1, participants performed "steady-state trials," in which environmental conditions remained constant during a trial, whereas in Experiment 2, participants performed "transition trials," in which sudden changes between conditions occurred during a trial.

Data Reduction and Analysis

The raw data 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 oscilla-

Table 1
Means of Dependent Variables in Experiment 1 for the Five Conditions in Session A and Session G

Sessions	Condition 1	2	3	4	5
Session A					
Alpha values	0.55	0.53	0.48	0.45	0.41
Error (ε, cm)	1.70 (0.38)	1.91 (0.50)	1.81 (0.46)	1.98 (0.47)	1.95 (0.34)
Racket velocity at impact (v_r, m/s)	0.90 (0.04)	0.97 (0.05)	1.08 (0.04)	1.16 (0.05)	1.25 (0.06)
Racket period (T_r, s)	0.66 (0.02)	0.66 (0.02)	0.66 (0.02)	0.66 (0.02)	0.65 (0.02)
Racket amplitude (A_r, cm)	16.3 (2.0)	17.5 (2.5)	19.4 (1.8)	20.6 (2.0)	22.0 (2.4)
Impact phase (ϕ_r, deg)	288.2 (9.9)	289.2 (6.7)	290.7 (7.0)	290.7 (6.9)	290.8 (6.8)
Impact height (h_c, cm)	2.0 (2.9)	2.4 (3.0)	1.7 (2.8)	1.5 (3.2)	2.4 (2.8)
Racket acceleration at impact (a_r, m/s^2)	−0.35 (2.32)	−0.68 (2.32)	−1.41 (3.19)	−1.20 (3.43)	−2.54 (3.70)
Session G					
Gravity values	6.56	8.10	9.81	11.66	13.69
Error (ε, cm)	2.10 (0.76)	1.96 (0.78)	1.70 (0.38)	1.85 (0.54)	2.27 (0.47)
Racket velocity at impact (v_r, m/s)	0.90 (0.05)	0.98 (0.06)	1.07 (0.07)	1.18 (0.08)	1.28 (0.07)
Racket period (T_r, s)	0.80 (0.04)	0.72 (0.03)	0.66 (0.03)	0.61 (0.03)	0.57 (0.02)
Racket amplitude (A_r, cm)	20.0 (3.0)	19.9 (3.4)	18.9 (2.7)	19.1 (3.1)	18.7 (3.0)
Impact phase (ϕ_r, deg)	299.1 (12.1)	295.7 (12.4)	293.3 (6.5)	289.6 (7.1)	289.8 (6.1)
Impact height (h_c, cm)	2.4 (4.7)	2.5 (4.4)	2.4 (4.2)	0.2 (3.7)	0.3 (3.3)
Racket acceleration at impact (a_r, m/s^2)	−2.03 (2.11)	−2.16 (3.57)	−1.3 (2.41)	0.14 (2.12)	1.78 (2.83)

Note. Values in parentheses are standard deviations.

tion, and ball/racket impact. Performance was characterized by the error in bouncing to the target (ε) defined as the difference between the midpoint of the ball at its peak position and target height, and by the racket velocity at impact (v_r). Racket oscillation was characterized by the cycle period (T_r), defined as the time between two successive peak racket positions, and racket cycle amplitude (A_r), defined as the difference between successive valley and peak racket positions (Sternad et al., 2001; De Rugy, et al., 2003). Ball/racket impact was characterized by the phase in the racket cycle at impact (ϕ_r), calculated as the ratio between the time of impact in the racket cycle and the cycle period, and the racket acceleration at impact (a_r).

A racket cycle (C_i) was defined by two successive maximum racket positions (see Figure 1). For convenience, racket cycles were numbered from a discrete event such as a transition or an impact, where C_0 refers to the cycle that immediately follows the key event, C_{-1} refers to the preceding cycle, and $C_1, C_2 \ldots$, refer to the subsequent cycles (Figure 1).

Experiment 1: Steady-State Bouncing

In Experiment 1, we examined how racket oscillation depends on environmental parameters g and α during steady-state bouncing. We manipulated g and α between trials but held their values constant within a trial. Our first aim was to determine whether racket parameters can be independently controlled, to gain insight into appropriate model oscillators. We expected higher values of g to yield a compensatory decrease in racket period, and perhaps corresponding shifts in racket amplitude and/or impact phase. Conversely, we expected higher values of α to yield a compensatory decrease in racket amplitude but no change in racket period. Finally, if participants exploit passive stability, we would expect the impact acceleration to remain in the passive range.

Our second aim was to begin investigating the coupling of informational variables in the ball's trajectory to parameters of racket oscillation. Recall that the informativeness of launch velocity and peak height depend on an implicitly known value of g, whereas that of flight period does not; these variables are thus dissociated by varying g. Consequently, correlations between variables of the ball's trajectory and variables of racket motion computed across g conditions may reveal the information used to control bouncing, under the assumption that participants do not rapidly learn a new value of g during one trial.

Method

In Session A and Session G, subjects first performed two practice trials in the reference condition, followed by one test trial in each of the five environment conditions in a random order. Each trial lasted 40 s. For analysis, the first 8 s of data were removed from each trial to eliminate transients. The dependent variables were then measured for each remaining racket cycle, and these values were averaged to yield means for each trial.

Results

Data from a representative participant are presented in phase portraits (non-normalized) in Figure 3, which plot racket velocity as a function of racket position. Note that impact (black crosses) tends to occur near or just after the peak (upward) racket velocity, and that the size and shape of the portrait change systematically with g and α. A summary of the means and standard deviations of all dependent variables appears in Table 1.

Task performance: error and racket velocity at impact. Participants could sustain quite accurate bouncing under all conditions, with constant errors around +2 cm and standard deviations about 0.5 cm. Looking first at the mean bouncing error (ε), participants bounced the ball approximately 2 cm above the target, consistent with aligning the bottom of the 4 cm diameter ball with the target line. A two-way repeated measures analysis of variance

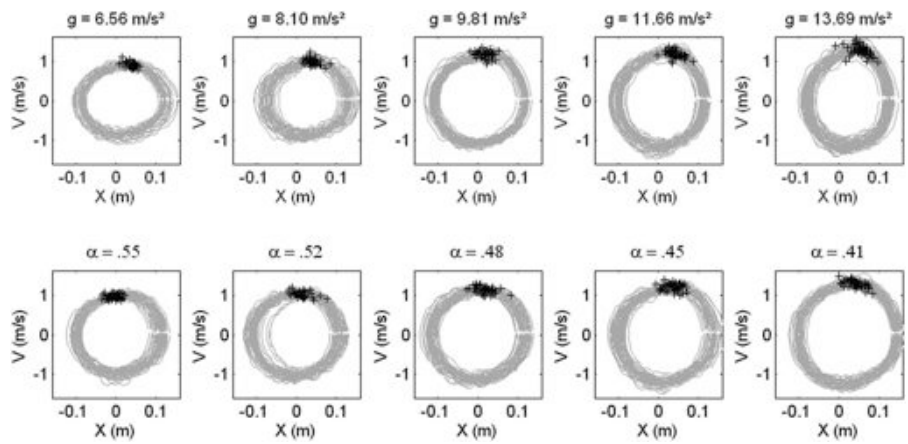

Figure 3. Nonnormalized phase portraits of racket motion (velocity as a function of position) from a representative participant in Experiment 1. Plots depict the steady-state trial in each condition of Session G (top row) and Session A (bottom row). Individual racket cycles were centered on the x axis; time runs clockwise; crosses indicate impacts.

(ANOVA) on ε (2 sessions × 5 conditions) yielded no significant main effect of condition, $F(1, 12) = 1.45$, $p > .05$, $\eta^2 = 0.10$, or session, $F(4, 48) = 1.84$, $p > .05$, $\eta^2 = 0.13$, but a significant interaction, $F(4, 48) = 2.90$, $p = .03$, $\eta^2 = 0.20$. However, post-hoc pairwise comparisons identified no significant differences between Session A and Session G for any of the five conditions, so performance in the two sessions can be considered similar.

Racket velocity at impact is highly constrained by the task, and the conditions were designed so that impact velocity would increase from Cd1 to Cd5, with similar values in both sessions. A repeated-measures ANOVA on impact velocity (2 sessions × 5 conditions) confirmed a significant main effect of condition, $F(4, 48) = 589$, $p < .0001$, $\eta^2 = 0.98$, but not session, $F(1, 12) = 0.68$, $p > .05$, $\eta^2 = 0.05$, with no significant interaction, $F(4, 48) = 1.34$, $p > .05$, $\eta^2 = 0.10$. Post-hoc tests (Neuman-Keuls) showed no significant differences between sessions for any of the five conditions. This confirms that racket parameters were adjusted to achieve the impact velocity required to maintain successful bouncing as environmental conditions were varied.

Impact variables. The phase of impact in the racket cycle was constant in Session A, but varied slightly in Session G (Table 1, Figure 4b). A repeated-measures ANOVA on impact phase (2 sessions × 5 conditions) showed no significant main effect of session, $F(1, 12) = 2.16$, $p > .05$, $\eta^2 = 0.15$, or condition, $F(4, 48) = 1.63$, $p > .5$, $\eta^2 = 0.12$, but did reveal a significant interaction, $F(4, 48) = 6.04$, $p < .001$, $\eta^2 = 0.33$. For Session G, post-hoc analyses confirmed a significant difference between mean impact phase in Cd1 (299.1 ± 12.1 deg) and each of the following conditions: Cd3 (293.3 ± 6.5 deg), Cd4 (289.6 ± 7.1 deg), and Cd5 (289.8 ± 6.1 deg). In other words, impact occurred

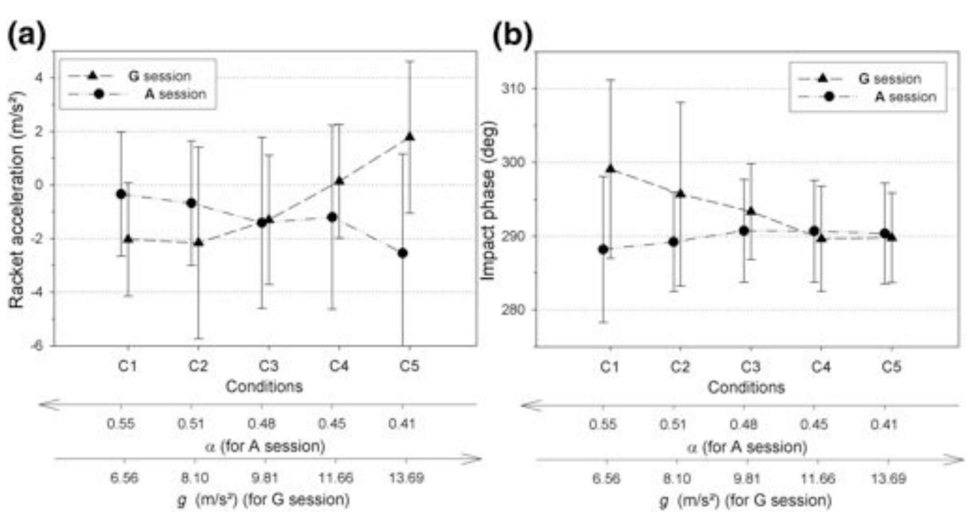

Figure 4. Means (±1 SD) of impact acceleration and phase for steady-state trials in each condition of Experiment 1. (a) Racket acceleration at impact. (b) Racket phase at impact. Conditions C1 to C5 denote the values of α shown below for Session A, and those of *g* shown below for Session G.

earlier in racket cycle with higher values of g, when ball and racket motion were faster. On the other hand, there were no significant differences between the five conditions in Session A. Thus, consistent with expectations, impact phase advanced slightly with an increase in g, but did not vary with α.

Racket acceleration at impact is an integrative variable in that it depends on racket period, amplitude, and impact phase, and serves as an index of the passive stability regime (Table 1, Figure 4a). For the reference condition Cd3, the mean impact acceleration was -1.31 ± 2.42 m/s^2 in Session G and -1.41 ± 3.19 m/s^2 in Session A, both within the negative, passively stable region. Indeed, mean acceleration was in the passively stable range in all conditions except Cd4 and Cd5 of Session G. A repeated-measures ANOVA showed no main effect of session, $F(1, 12) = 0.46$, $p > .05$, $\eta^2 = 0.03$, but a significant main effect of condition, $F(4, 48) = 2.66$, $p < .05$, $\eta^2 = 0.18$, and a significant interaction, $F(4, 48) = 12.1$, $p < .01$, $\eta^2 = 0.50$. Indeed, in Session G impact acceleration increased monotonically from Cd1 to Cd5 (i.e. as g increased). Post-hoc tests showed that mean racket acceleration in Cd4 was significantly different from that in Cd1, Cd2, and Cd5, and racket acceleration in Cd5 was significantly different from that in the four other conditions ($p < .05$). Conversely, in Session A mean racket acceleration at impact tended to decrease from Cd1 to Cd5 (as α decreased), although post-hoc tests did not find significant differences. In other words, consistent with the analysis of phase, impact acceleration tended to stay in the passively stable region but was not constant, moving out of the passive range as gravity increased. Moreover, accurate bouncing could also be maintained outside of the passively stable regime.

Oscillator variables. As expected, racket period remained constant over variation in α in Session A, whereas it decreased as g increased in Session G (Table 1, Figure 5a). A 2-way repeated-measures ANOVA on racket period (2 sessions $\times$ 5 conditions) showed main effects of session, $F(1, 12) = 10.88$, $p < .01$, $\eta^2 = 0.47$, and condition, $F(4, 48) = 224.6$, $p < .0001$, $\eta^2 = 0.95$, and most importantly a significant interaction, $F(4, 48) = 197.5$, $p < .0001$, $\eta^2 = 0.94$. Post-hoc test (Neuman-Keuls) revealed that the five means in Session G were all significantly different from one another, whereas there were no statistically significant differences among the five conditions in Session A.

The pattern was reversed for racket amplitude (Table 1, Figure 5b). In Session A, racket amplitude increased from Cd1 to Cd5 (as α decreased) in order to achieve the required increase in impact velocity, given that racket period remained constant. In Session G, by contrast, there were only minor adjustments in racket amplitude from Cd1 to Cd5 (as g increased) because the required increase in impact velocity could largely be achieved by a decrease in racket period. A repeated-measures ANOVA on amplitude (2 sessions $\times$ 5 conditions) showed no main effect of session, $F(1, 12) = 0.06$, $p > .05$, $\eta^2 = 0.00$, a main effect of condition, $F(4, 48) = 17.54$, $p < .0001$, $\eta^2 = 0.59$, and a significant interaction, $F(4, 48) = 50.67$, $p < .0001$, $\eta^2 = 0.81$. For Session A, Neuman-Keuls post-hoc test showed that the five condition means were significantly different from one another. For Session G, only the mean in Cd5 was significantly smaller than Cd1 and Cd2.

In sum, as expected, an increase in g elicited a decrease in racket period accompanied by minor adjustments in racket amplitude and impact phase, whereas an increase in α elicited a decrease in racket amplitude with no change in racket period or phase.

Finally, since the reference condition was the same in both Sessions, we checked to make sure that bouncing behavior was not influenced by the session context. Post-tests for the ANOVAs described above indeed showed no significant difference in the dependent variables (error, racket velocity, period, amplitude, impact phase, impact acceleration) between Cd3 of Session G and Cd3 of Session A.

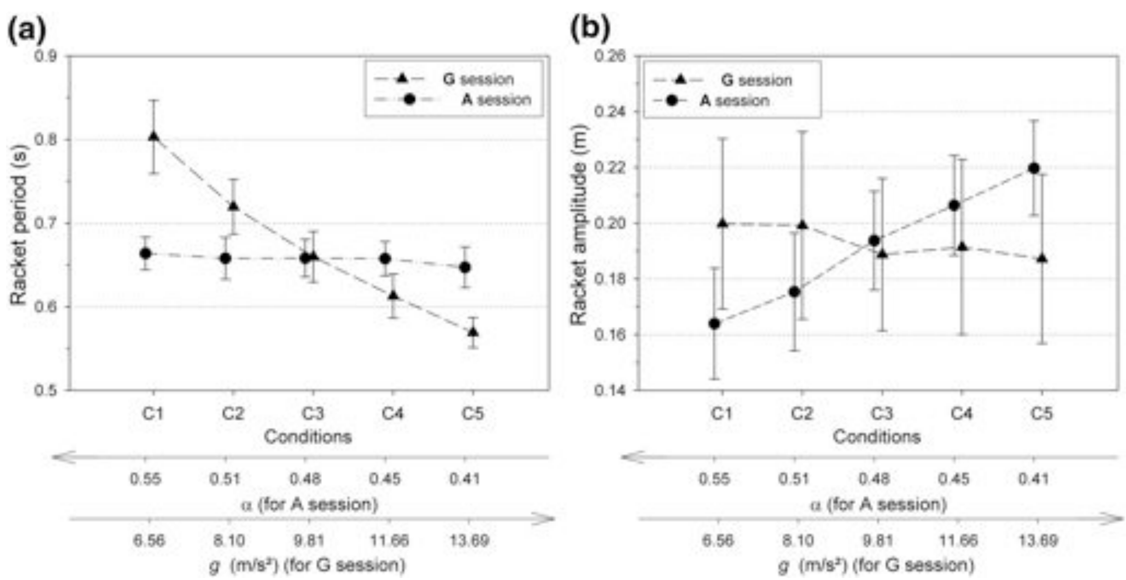

Figure 5. Means (± 1 SD) of racket cycle period and amplitude in steady-state trials of Experiment 1. (a) Racket period in each condition of Session G and A. (b) Racket amplitude in each condition of Session G and A. Conditions C1 to C5 denote the values of α shown below for Session A, and those of g shown below for Session G.

Covariation of oscillator variables. In order to assess the dependencies among racket oscillator variables, correlations and linear regressions were performed between racket amplitude (A_r), racket frequency (ω_r), and peak racket velocity (v_{max}) on every cycle (we tested frequency rather than period to be comparable with the literature on rhythmic movement). In Session A, where racket amplitude decreased with α but g remained constant, there was no correlation between amplitude and frequency ($N = 65$, $R = -0.05$, $R^2 = 0.003$). In contrast, in Session G, where racket frequency increased with g, we find a significant negative correlation between amplitude and frequency ($N = 65$, $R = -0.33$, $R^2 = 0.11$, $A_r = 0.27 - 0.05\ \omega_r$, $p < .01$). However, the correlation coefficient is quite small, reflecting the constraints on amplitude for the task of bouncing to a target height. This analysis confirmed the observation that racket parameters for frequency and amplitude do not necessarily covary, but can be controlled independently.

Second, if racket motion is approximately harmonic [$y = (A_r/2)\cos(2\pi\omega_r t)$], we would expect that peak velocity is proportional to amplitude with a coefficient of $\pi\omega_r = 4.77\text{s}^{-1}$. Indeed, in Session A, peak velocity and amplitude were significantly correlated ($N = 65$, $R = 0.84$, $R^2 = 0.7$) with a regression slope close to the predicted value ($v_{max} = 0.31 + 4.44A_r$ m/s, $p < .001$). Similarly, in Session G, given that both frequency and impact velocity increased with g, it is not surprising to obtain a positive relationship between ω_r and v_{max} [$N = 65$, $r = .65$, $r^2 = 0.42$, $v_{max} = 0.39 + 0.52\ \omega_r$, $p < .001$].

Correlations Between Information Variables and Racket Oscillation

To analyze the modulation of racket motion by visual information, we performed correlations between ball variables after each impact and the amplitude and period of racket oscillation on the next three cycles. Recall that informational variables were dissociated by varying g, but not by varying α. Thus, correlations were computed across all trials in Session G, and separately across all trials in Session A.[1] The racket cycle following a given impact was labeled C_0 (refer to Figure 1). Analyzed ball variables included the duration of the upward (t_{up}) and downward (t_{down}) half-periods during C_0, the amplitude of upward and downward ball motion during C_0, the peak height during C_0 (these correlations are equivalent to those with target error),[2] and the launch velocity following impact (v_b). These ball variables were correlated separately with the racket period and racket amplitude of cycle C_0 and the two succeeding cycles (C_1, C_2).

Correlation coefficients (R) appear in Table 2. First, consider the modulation of racket period in Session A. Racket cycle C_0 is best correlated with the variables of the ball's upward (R, $\cong$0.87) and downward (R, $\cong$0.94) trajectory during the same cycle; in contrast, subsequent racket cycles are much less correlated with this ball trajectory. This reveals that racket oscillation is actively controlled on a cycle-to-cycle basis by information from the concurrent flight of the ball. Specifically, it suggests that racket period is adjusted using information from the ball's upward half-period and fine-tuned just before impact using information from the downward flight. Because mean impact acceleration was negative in all conditions, these high correlations imply that racket period was actively controlled by information about the ball even in the passively stable region.

Second, consider modulation of racket period in Session G, when informational variables were dissociated. It is apparent that the C_0 racket period is highly correlated with the duration of the ball's upward ($R = .97$) and downward ($R = .98$) half-period during the same cycle. Importantly, correlations with the ball's peak height ($R = .43$) and launch velocity ($R = -.46$) are much lower. Note also that the correlations between ball flight period and racket period decline on subsequent cycles (C_1, $R = .80$; C_2, $R \cong .76$), although they remain high presumably because a constant g yields a similar racket period across cycles. This indicates that participants achieve sustained bouncing by using information about the ball's flight period (or possibly rate of gap closure) to modulate racket period in the concurrent cycle.

Finally, the correlations between ball variables and racket amplitude are all very low ($R \leq 0.25$). This is notably so for target error (i.e. peak height, $R < .07$), indicating that error does not serve to modulate either racket amplitude or period on the current or subsequent cycles.

Discussion

Participants can sustain quite accurate bouncing under variation in two major environmental parameters, the coefficient of restitution and gravitational acceleration. To produce the required impact velocity under different combinations of α and g, they systematically adjusted the kinematics of racket oscillation. In Session A, racket amplitude decreased as α was increased, while racket period and phase remained constant to match the constant g. In Session G, by contrast, racket period decreased as g was increased, to match the ball's flight period; this was accompanied by a small increase in racket amplitude. In addition, there was a minor advance in impact phase and a corresponding increase in impact acceleration, which became positive (not passively stable) at high values of g.

These results lead to four main conclusions. First, participants are able to maintain accurate bouncing outside the passively stable regime, when impact acceleration is positive. This confirms that bouncing can be actively stabilized on the basis of visual information, consistent with previous reports (Siegler et al., 2003; Morice et al., 2007). It does not appear that participants prefer to stay in the passive range under all conditions, for impact acceleration spontaneously increases to positive values with abnormally high values of g. Under all other conditions, however, bouncing is kept within the passively stable region.

Second, oscillator parameters for racket period and amplitude can be controlled independently. In Session G, racket period varied inversely with g while racket amplitude was approximately constant; conversely, in Session A, racket amplitude varied inversely

[1] This analysis is valid because racket motion is physically independent of ball motion and error is free to occur. Even for sustained bouncing, the racket period is not necessarily correlated more strongly with ball period than, for example, with peak height, because the racket phase at impact can vary and error can accumulate until control is lost or a correction is made. Which ball variables are coupled to racket motion is thus an empirical question.

[2] Note that a linear relationship is expected between racket period and the square-root of ball height (Equation 4). However, given the limited range of variation, ball peak height and square-root of peak height were highly correlated ($R^2 > 0.99$). As a consequence, correlations between each racket variable and ball height were very similar to those with the square-root of ball height ($R^2 \pm 0.01$), so we only report the former.

Table 2
Correlations Between Ball Variables and Racket Variables in Experiment 1, for Three Successive Racket Cycles in Session A and Session G

	All conditions					
	Racket cycle period			Racket cycle amplitude		
Session	C_0	C_1	C_2	C_0	C_1	C_2
Session A						
Ball variables						
Up half-period (t_{up0})	.86	.32	.20	.05	−.06	−.03 (ns)
Down half-period (t_{down0})	.93	.32	.22	.04	−.06	−.03 (ns)
Peak height (h_p)	.81	.17	.05	−.02	−.13 (ns)	−.10
Launch velocity (v_b)	.87	.32	.21	.05	−.06	−.03 (ns)
N	2,810					
Session G						
Ball variables						
Up half-period (t_{up0})	0.97	0.80	0.75	0.25	0.21	0.23
Down half-period (t_{down0})	0.98	0.80	0.76	0.25	0.21	0.24
Peak height (h_p)	0.43	0.06	−0.02 (ns)	0.07	−0.02 (ns)	0.04
Launch velocity (v_b)	−0.46	−0.61	−0.65	0.02 (ns)	−0.02 (ns)	0.00 (ns)
N	2,781					

Note. Unless indicated otherwise (not significant [ns]), all correlations are significant ($p < .05$). N = Number of studied cycles; C_0 = cycle that immediately follows the key event; C_1, C_2 = subsequent cycles.

with α while racket period remained constant. This was a consequence of the task constraints, for it was advantageous for racket period to match the flight period of the ball determined by a constant *g*, in which case racket amplitude had to vary with α too for the ball to reach the target. We did observe a small inverse relationship between frequency ($\omega_r = 1/T_r$) and amplitude in Session G, as amplitude decreased slightly in Cd5, consistent with previous results for unconstrained rhythmic movement (Kay et al., 1987; Beek et al., 1996). However, there was no such relationship in Session A. These results imply that a model of unconstrained movements in which frequency and amplitude are coupled and controlled by a single parameter, such as the stiffness coefficient in the hybrid Rayleigh-van der Pol (Kay et al., 1987), would not simply transfer to movements with strong task constraints. At least two control parameters that independently modulate frequency and amplitude are called for.

Third, racket oscillation is actively controlled on a cycle-by-cycle basis. High correlations between ball and racket variables indicate that information about the ball's trajectory influences racket oscillation *in the same cycle*. It is important to point out that these cycle-by-cycle adjustments occurred during steady-state bouncing in the passively stable region. This is consistent with the mixed control hypothesis, in which perceptual regulation plays a continuous role, rather than the hybrid control hypothesis, in which active adjustments only occur to correct for perturbations outside the stable range.

Finally, we can draw some preliminary conclusions about the visual information that is used to control racket parameters. Ball-racket correlations indicate that racket period is modulated by the durations of the upward and downward ball flight in the same cycle, rather than by its peak height or launch velocity. This result suggests that the ball's ascending half-period regulates a parameter controlling the frequency of racket oscillation. Such an informational coupling would explain how participants successfully matched racket period to ball period under varying gravitational conditions. In addition, it is possible that the tau-gap during the ball's descent might be used to fine-tune the racket period, although this result could also be due to the necessary correlation between the upward and downward half-periods of the ball's flight. We seek to test this question in Experiment 2. On the other hand, racket amplitude does not seem to be regulated by any of the studied ball variables including, somewhat surprisingly, error to the target on one bounce.

This analysis depends on the fact that informational variables were dissociated by varying *g* between trials and assumes that participants do not learn a new value of *g* during a 40-s trial, consistent with McIntyre et al. (2001). But if they were able to do so, the present pattern of correlations could result from reliance on peak height or launch velocity corrected by an implicitly known value of *g* (Equations 3 and 4). Thus, in Experiment 2 we probed the informational variables by applying sudden changes in *g* and α within a trial and analyzing immediate adjustments in racket oscillation.

Experiment 2: Adaptation to Sudden Changes

In Experiment 2, we investigated the control of bouncing by randomly changing an environmental parameter during ongoing bouncing, referred to as transition trials. The purpose of the experiment was twofold: to determine the mode of perceptual control and the information it relies on.

First, we sought another test of the hypotheses of passive and active control by determining whether the racket oscillation is adjusted within one cycle following a sudden change in *g* or α. Some transitions are *destabilizing*, in that they take the system into the unstable region, while others are *stabilizing*, in that they bring (or leave) the system into the passively stable region. On the pure active control hypothesis, we would expect rapid adjustments after all transition types, but they may or may not act to move the system into the stable range. On the mixed control hypothesis, adjustments following destabilizing transitions should move the system back into the passively stable range, and those following stabilizing transitions should keep the system in that range. Finally, on the hybrid control hypothesis, we would expect active adjustments only after destabilizing transitions, not stabilizing transitions.

Our second purpose was to probe the visual information used to regulate racket adjustments. The results of Experiment 1 suggest that racket period is modulated by the ball's flight period in the same racket cycle, assuming that participants did not learn the new value of g within one trial. Here we conduct a more sensitive test by measuring ball-racket correlations in the first few racket cycles after a transition, before participants had time to interact with the ball and learn the new value of g. If participants take significantly longer to recover steady-state performance in Session G than in Session A, it would suggest that they use visual information that depends on g to control bouncing; if there is no difference between Sessions, it would suggest that the effective information does not depend on g.

Moreover, correlations between ball and racket variables immediately after a g transition may reveal the information used. If participants rely on peak height or launch velocity, their correlations with racket period should be high in the first cycle after a transition, while the correlations between flight period and racket period should be lower, resulting in increased error. Conversely, if participants rely on the duration of the ball's upward half-period or gap closure during the downward half-period, their correlations with racket period should be higher than those for peak height and launch velocity. In contrast, all correlations should be relatively strong following an α transition, because it does not dissociate the information.

Methods

The five environment conditions (Cd1 to Cd5) in Session A and Session G had the same values of g and α as in Experiment 1, so the required pre- and posttransition racket velocities were equated across sessions. Participants performed 12 transition trials in each session, with three transitions per trial. A trial lasted 80 s and was composed of four phases with durations of 16 or 24 s, thereby randomly varying the time between transitions. The first and third phases always presented the reference condition (Cd3, $g = 9.81$, $\alpha = .48$) whereas the second and fourth phases presented one of the other conditions. Thus, in Session G there were two small and two large transitions that increased g and two small and two large transitions that decreased g (see Table 3); correspondingly, in Session A there were four transitions that decreased α and four that increased α. Transitions from the reference condition to other conditions were each presented six times per session, and the reverse transitions were each presented three times per session.

In Session G, the value of g was changed at the ball's maximum position in racket cycle C_0, thereby dissociating its upward half-period from its downward half-period (refer to Figure 2). In Session A, the value of α was changed at the impact immediately before C_0. In the analysis, dependent variables were averaged across trials to yield a mean for the transition cycle (C_0), and for preceding (C_{-1}) and succeeding ($C_1, \ldots$) cycles. The two sessions occurred in a random order, and trials were presented in a random order within sessions.

Results

Stabilizing and destabilizing transitions. The mean acceleration on the last impact before (Impact −1) and first impact after (Impact 0) the transition is reported in Table 3 (see also Figure 6).

Table 3
Characteristics of Transitions in Experiment 2, Session A and Session G

Sessions	Transition type	N	Height $F(df)$	p	Plateau bounce	Racket acceleration before transition	Racket acceleration after transition
Session A							
Decrease α large	.55→.48	39	$F(8, 304) = 8.80$	$p < .0001^*$	3	−1.65 (5.16)	−1.21 (6.71)
Small	.52→.48	39	$F(8, 304) = 6.63$	$p < .0001^*$	2	−1.07 (6.03)	−0.04 (7.25)
Small	.48→.45[b]	78	$F(8, 616) = 4.82$	$p < .0001^*$	4	−1.09 (5.71)	−1.59 (6.31)*
Large	.48→.41	78	$F(8, 616) = 18.4$	$p < .0001^*$	4	−0.70 (6.04)	0.45 (8.32)
Increase α large	.41→.48[b]	39	$F(8, 304) = 10.0$	$p < .0001^*$	2	−1.35 (6.28)	−2.66 (5.74)*
Small	.45→.48[b]	39	$F(8, 304) = 1.68$	$p = .1$	0	−0.89 (7.12)	−1.98 (5.11)*
Small	.48→.52[b]	78	$F(8, 616) = 6.26$	$p < .0001^*$	2	−0.55 (6.45)	−2.37 (5.80)*
Large	.48→.55[b]	78	$F(8, 616) = 13.8$	$p < .0001^*$	4	−0.10 (5.72)	−2.40 (5.43)*
Session G							
Increase g large	6.56→9.81[a]	39	$F(8, 304) = 15.3$	$p < .0001^*$	2	−1.76 (5.46)	4.52 (4.03)*
Small	8.10→9.81[a]	39	$F(8, 304) = 5.65$	$p < .0001^*$	1	−1.53 (4.38)*	1.77 (4.08)*
Small	9.81→11.66[a]	78	$F(8, 616) = 6.71$	$p = .01^*$	3	−0.93 (5.52)	2.91 (6.32)*
Large	9.81→13.69[a]	78	$F(8, 616) = 41.7$	$p < .0001^*$	5	−1.55 (6.51)*	5.66 (5.98)*
Decrease g large	13.69→9.81[b]	39	$F(8, 304) = 3.54$	$p < .001^*$	1	3.39 (7.82)*	−8.88 (6.36)*
Small	11.66→9.81[b]	39	$F(8, 304) = 5.08$	$p < .0001^*$	1	0.42 (5.98)	−3.78 (5.98)*
Small	9.81→8.10[b]	78	$F(8, 616) = 2.34$	$p = .02^*$	1	0.47 (6.51)	−4.86 (5.92)*
Large	9.81→6.56[b]	78	$F(8, 616) = 1.71$	$p = .09$	0	−0.15 (6.51)	−7.56 (4.43)*

Note. Number of transitions (N). Results of ANOVAs on error (cycles 0 to 8) for each transition type; number of cycles after C_0 before plateau of accurate bouncing is reached; and mean racket acceleration at impact during C_{-1} (before transition) and C_0 (after transition).
[a] Take out of stable region. [b] Bring into stable region.
* Significant change in error across cycles.

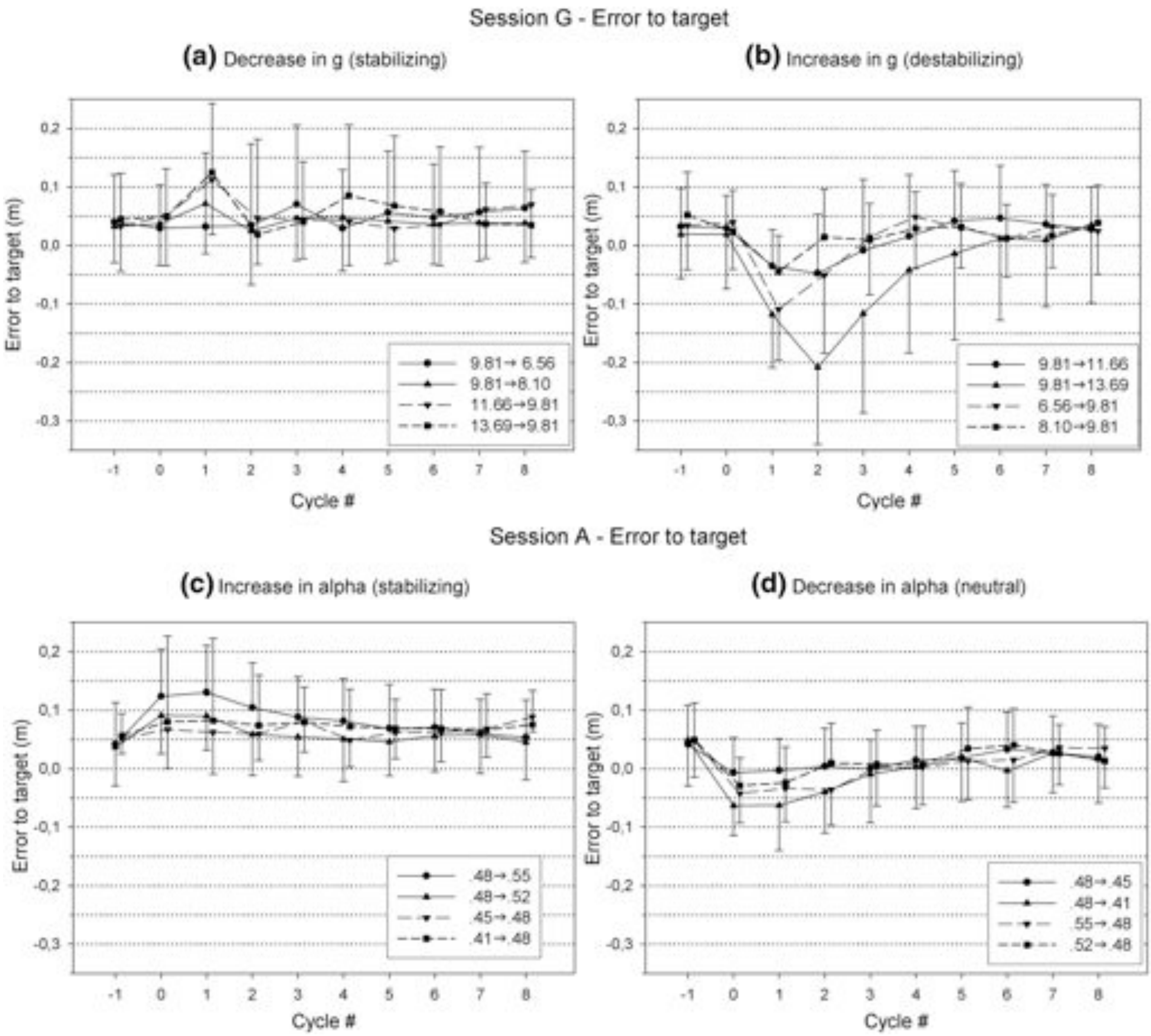

Figure 6. Means ($\pm$1 SD) of the racket acceleration at impact for each transition type in Experiment 2, as a function of impact number. (a) Decreases in *g* (stabilizing), (b) increases in *g* (destabilizing), (c) increases in α (stabilizing), (d) decreases in α (neutral). Impact *i* takes place during C_i. The α transition occurs at Impact -1; the *g* transition occurs at ball peak between Impact -1 and Impact 0.

To classify transition types as stabilizing or destabilizing, we performed one-sample *t* tests to determine whether the mean impact acceleration before and after the transition was statistically different from zero (see Table 3). In Session G, all four increases in *g* were destabilizing, taking the system into the significantly positive range ($p < .05$), whereas all four decreases in *g* were stabilizing, bringing the system into the significantly negative range ($p < .05$). In Session A, none of the transitions were significantly destabilizing, whereas all increases in α and one decrease (.48→.45) were stabilizing, bringing the system into the significantly negative range ($p < .05$); the other three transitions were neutral, not significantly different from zero before or after the transition. Note that impact acceleration tended to return toward the negative range following a destabilizing transition (Figure 6b) and remain in the negative range after a stabilizing transition (Figure 6a, c).

Relaxation time to recover accurate bouncing. The mean target error in each condition appears in Figure 7, plotted as a function of the racket cycle in which the peak of the ball's flight occurred. For Session G, panel (a) presents decreases in *g*, which were stabilizing, and panel (b) presents increases in *g*, which were destabilizing. Note that the ball tended to overshoot the target after a decrease in *g*, and vice versa, then return to pretransition accuracy over the next several bounces. For Session A, panel (c) plots

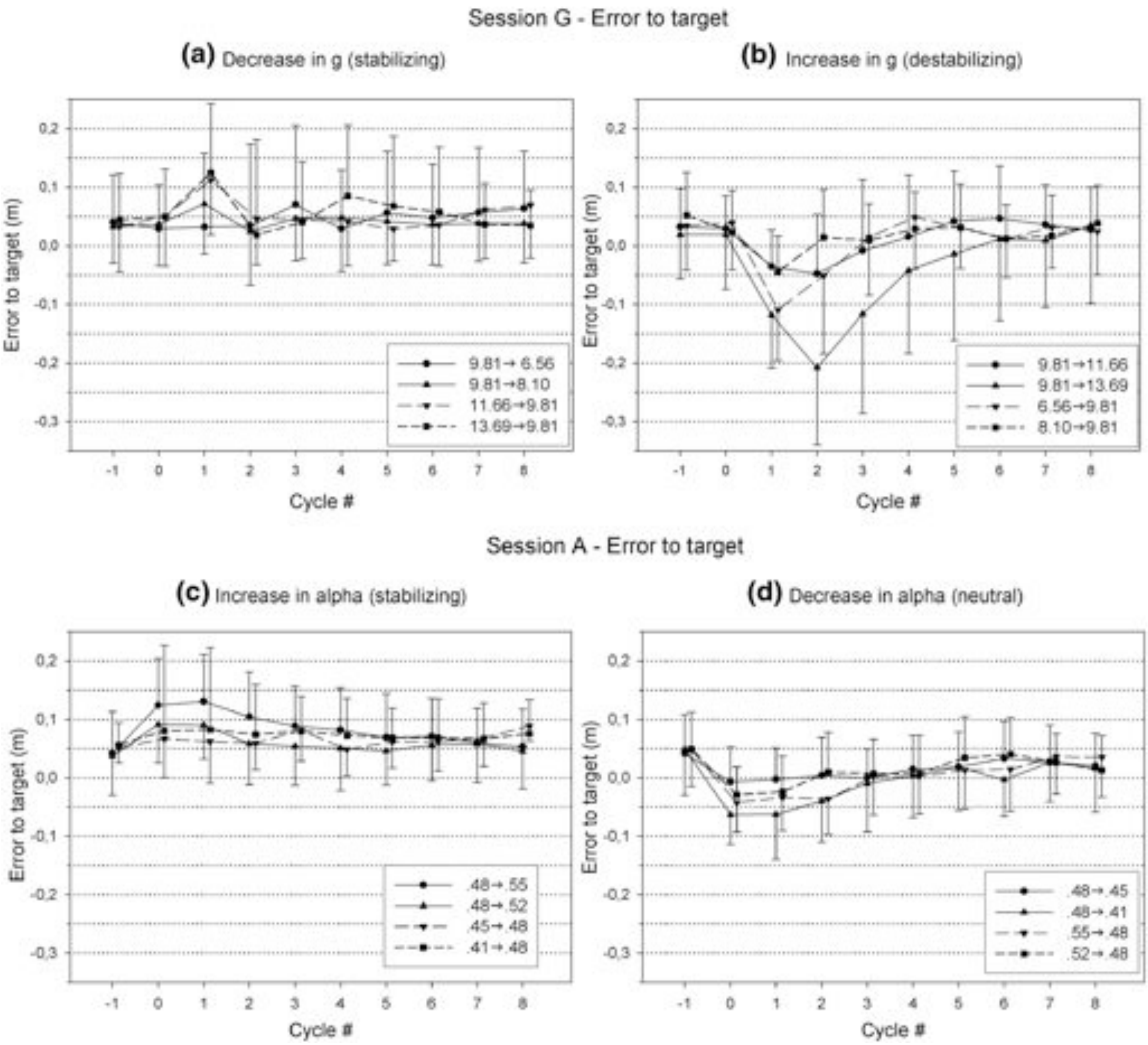

Figure 7. Means (±1 SD) of target error (ε) for each transition type in Experiment 2 as a function of cycle number. (a) Decreases in *g* (stabilizing), (b) increases in *g* (destabilizing), (c) increases in α (stabilizing), (d) decreases in α (neutral). The α transition occurs at impact just prior to C_0; the *g* transition occurs at the ball peak during C_0.

increases in α, which were stabilizing, and panel (d) plots decreases in α, one of which was also stabilizing (.48→.45) and the rest neutral. In this case, the ball tended to overshoot the target after an increase in α, and vice versa, then recover over the next few bounces.

To assess the number of cycles needed to recover accurate bouncing, we performed one-way repeated-measures ANOVAs on error (cycles 0 to 8) separately for each transition type (see Table 3). Neuman-Keuls post-hoc tests were then used to determine the first bounce cycle following C_0 that was not significantly different from the succeeding cycles, to specify when bouncing returned to a plateau level. In Session G, there was a significant change in error on seven of the eight *g* transitions, and performance plateaued after two bounces, on average. In Session A, there was a significant change in error on seven of the eight α transitions, and performance plateaued after three bounces, on average. Participants thus recovered accurate bouncing as rapidly (if not faster) after a change in *g* as they did after a change in α, implying that they did not need to learn the new gravitational constant in order to make adaptive adjustments.

The results also indicate that greater destabilization required a longer relaxation time. In Session G, the Pearson correlation between the first post-transition impact acceleration and the number of bounces to plateau was $r = .77$. In Session A, the correlation was only $r = .26$, reflecting the absence of destabilization and the narrow range of impact accelerations.

Racket adjustments. To test active and passive stabilization, we examined racket adjustments following the transition. To normalize racket motion across conditions, we first determined reference values of racket period by averaging the three pretransition cycles (C_{-3} to C_{-1}), and then computed ratios of racket period over the reference value for racket cycles C_{-1} to C_8. A ratio of 1.0 indicates that a cycle period was equal to the pretransition reference value, and a ratio greater than 1.0 indicates it was larger than the reference value. This computation was repeated for racket amplitude.

Modulation of racket period (Figure 8) is apparent in the first complete cycle following the transition. To determine whether these adjustments were significantly greater than the expected value of 1.0, we performed planned comparisons on the mean ratio for each cycle (C_0 to C_4) using the Bonferroni correction ($p = .05/5 = 0.01$). In Session G, when the transition occurred at the peak of the ball's trajectory, its downward flight did not elicit a racket adjustment in the same cycle (C_0), but all transitions evoked a significant adjustment in the next cycle (C_1) ($N = 78$ or $N = 39$, $p < .01$). Moreover, the direction of adjustment was adaptive, in

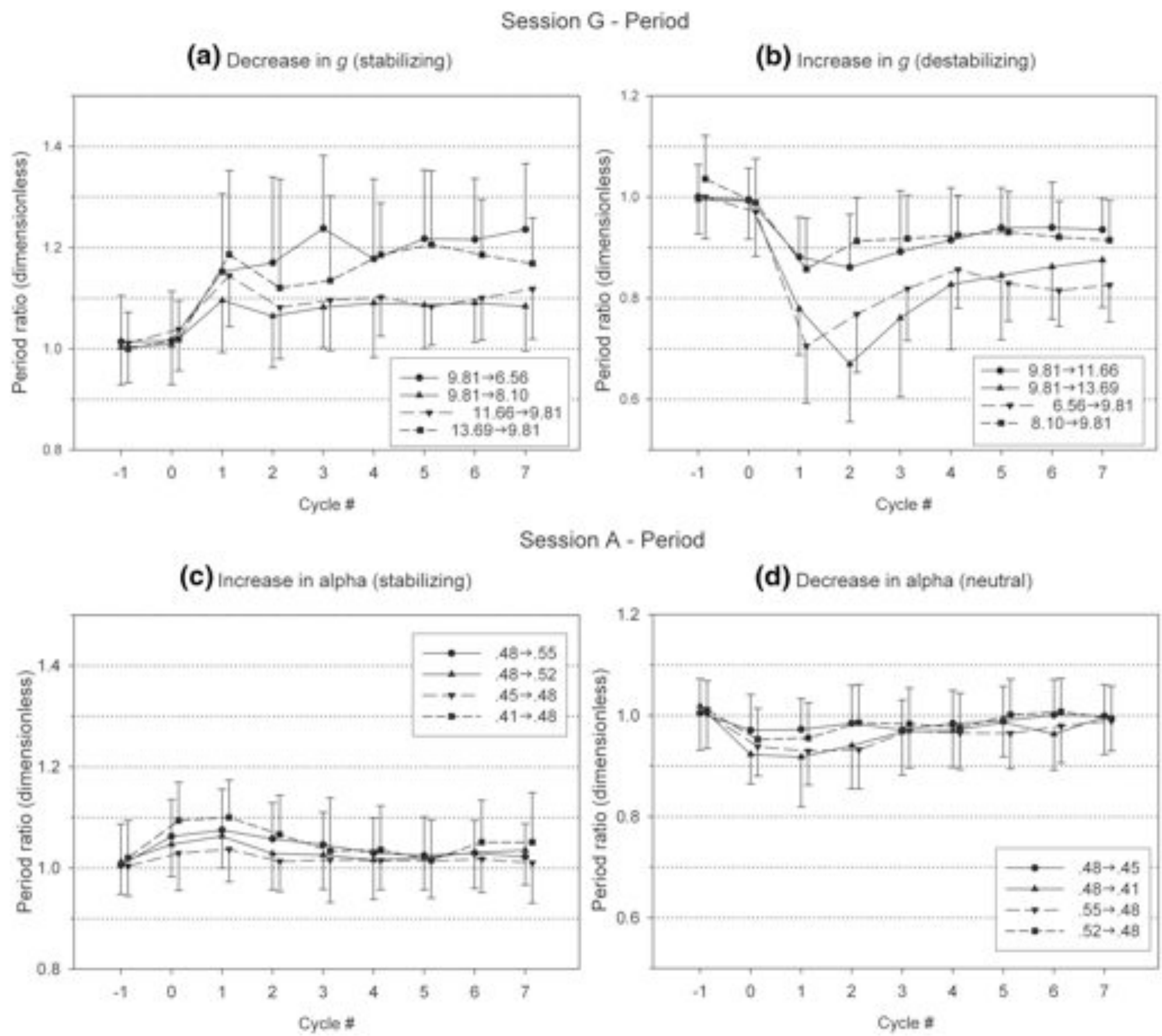

Figure 8. Means (±1 SD) of the racket period ratio for each transition type in Experiment 2, as a function of cycle number. (a) Decreases in g (stabilizing), (b) increases in g (destabilizing), (c) increases in α (stabilizing), (d) decreases in α (neutral). The α transition occurs at impact just prior to C_0; the g transition occurs at the ball peak during C_0.

that racket period increased with a decrease in *g* (Figure 8a), and vice versa (Figure 8b). In Session A, when the transition occurred at impact, the ball's complete flight was sufficient to elicit an adjustment in the same cycle (C_0) for all transition types ($N = 78$ or $N = 39$, $p < .01$). Again, the direction of adjustment was adaptive, in that racket period increased with an increase in α (Figure 8c), and vice versa (Figure 8d). Importantly, these racket adjustments occurred not only after destabilizing transitions (Figure 8a), but also after stabilizing transitions (Figure 8b, c) and neutral ones (Figure 8d) as well. Thus, participants rapidly and adaptively adjusted the period of the first complete racket cycle after a transition, whether it destabilized the system or not.

In contrast, modulation of racket amplitude (Figure 9) depended on condition. In Session G, significant adjustments in amplitude occurred in the first complete cycle after the transition (C_1) for all transitions ($N = 78$ or $N = 39$, $p < .01$), all in an adaptive direction (Figure 9a, b). Importantly, these rapid amplitude adjustments were again observed after stabilizing (Figure 9a) as well as destabilizing (Figure 9b) transitions. By contrast, in Session A amplitude adjustments were more gradual and only became significant in the second complete cycle (C_1) for all transition types ($N = 78$ or $N = 39$, $p < .01$) [Figure 9c, d]. This one-cycle delay in amplitude adjustments was not observed for period and compares with de Rugy et al.'s (2003) observation that variability in

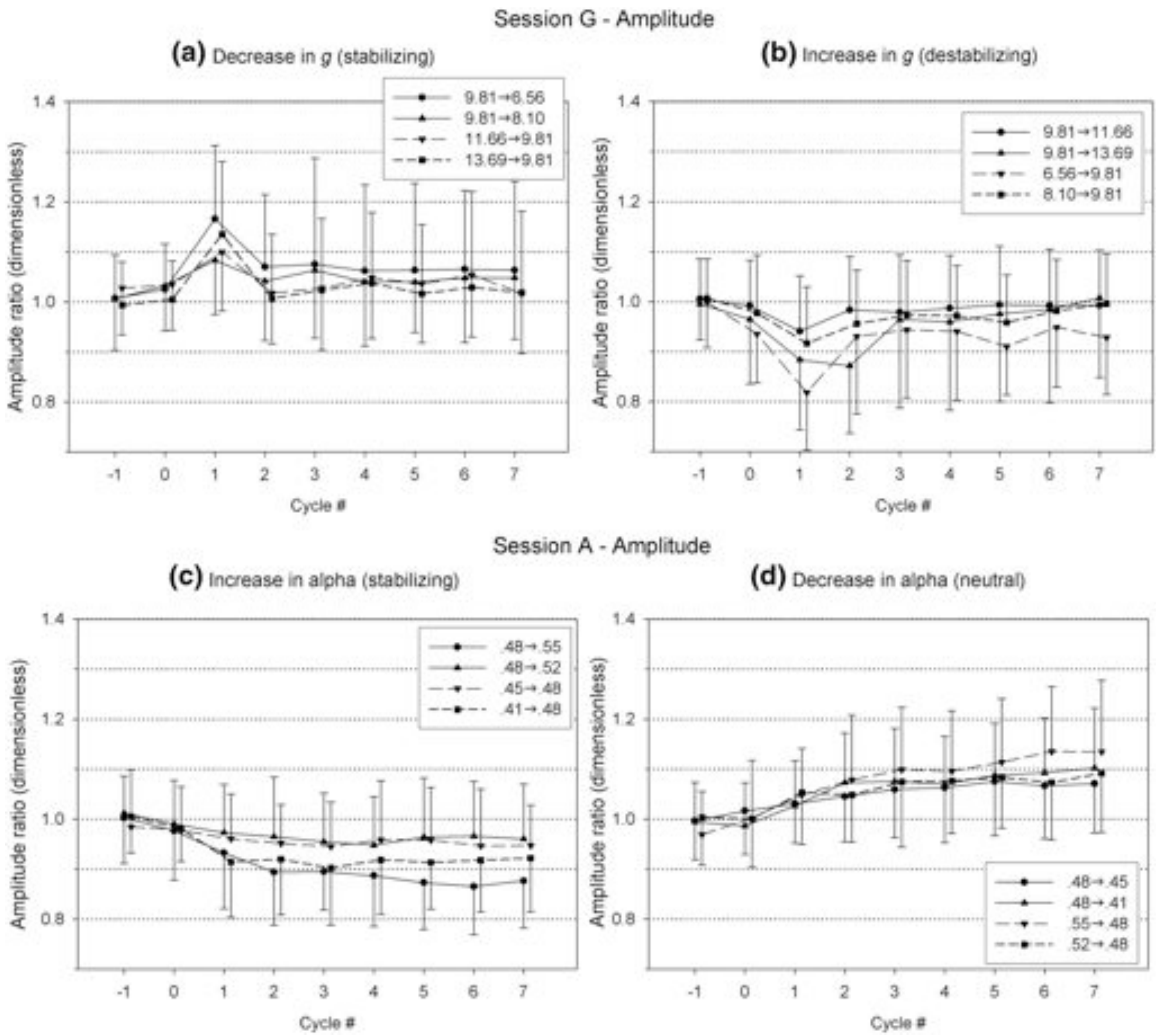

Figure 9. Means (± 1 SD) of the racket amplitude ratio for each transition type in Experiment 2, as a function of cycle number. (a) Decreases in *g* (stabilizing), (b) increases in *g* (destabilizing), (c) increases in α (stabilizing), (d) decreases in α (neutral). The α transition occurs at impact just prior to C_0; the *g* transition occurs at the ball peak during C_0.

racket amplitude peaked systematically in the second or third cycle after a perturbation in α.

Finally, note that racket period permanently shifted to a new value in Session G (C_1 to C_4, $p < .01$), reflecting adaptation to a new flight period (Figure 8a, b), whereas the shift was brief in Session A (C_1 to C_2, $p < .01$; C_3 to C_4, $p > .01$), reflecting a transitory response to a change in α that only briefly affected flight period (Figure 8c, d). Adjustments in racket amplitude were complementary to those in period: in Session A, amplitude permanently shifted to a new value (C_1 to C_4, $p < .01$), reflecting adaptation to a new α (Figure 9c, d), whereas in Session G the shift was generally brief (C_1, $p < .01$; C_3 to C_4, $p > .01$) except for the 9.81→6.56 and 9.81→8.10 transitions, reflecting a transitory response to a change in *g* that left the elasticity of the system constant (Figure 9a, b).

In sum, we observed rapid adjustments in both racket period and amplitude in the first complete cycle after a *g* transition, whereas we saw period adjustments in the first cycle and amplitude adjustments in the second cycle after a α transition. Such responses are inconsistent with the passive stabilization hypothesis. Moreover, the fact that rapid adjustments occurred after stabilizing as well as destabilizing transitions is inconsistent with hybrid control, but consistent with mixed control.

Onset of Racket Modulation

How quickly is racket oscillation adjusted in response to a transition? In Session G, when *g* was changed at the peak of the ball's trajectory (in C_0), it is possible that the ball's descent modulated the racket's upswing during C_0 even though it did not have a statistical effect on the full cycle period. We thus analyzed the third quarter-cycle of the upswing when the racket is accelerating (time elapsed from $v_r = 0$ to $v_r = v_r$ max), and the fourth quarter-cycle when it is decelerating (from $v_r = v_r$max to $v_r = 0$), comparing the pre-transition cycle (C_{-1}) and the transition cycle (C_0) for each transition type. First, a two-way repeated-measures ANOVA on the duration of the third quarter-cycle (2 cycles × 8 transition types) revealed a main effect of transition type, $F(7, 459) = 18.06$, $p < .0001$, $\eta^2 = 0.22$, but no main effect of cycle, $F(1, 459) = 0.47$, $p > .05$, $\eta^2 = 0.00$, and no interaction, $F(7, 459) = 0.63$, $p > .05$, $\eta^2 = 0.00$. Post-hoc analyses (Neuman Keuls) showed no difference between transition and pre-transition cycles for any transition type. Thus, it does not appear that the third quarter-cycle was influenced by the ball's descent.

However, a similar ANOVA on the duration of the fourth quarter-cycle revealed a significant main effect of transition type, $F(7, 459) = 16.48$, $p < .0001$, $\eta^2 = 0.20$, a marginal effect of cycle, $F(1, 459) = 3.19$, $p = .07$, $\eta^2 = 0.00$, and a significant interaction, $F(7, 459) = 9.36$, $p < .0001$, $\eta^2 = 0.13$. Specifically, post-hoc analyses (Neuman Keuls) showed that, with large increases in *g* that called for decreases in racket period, the last quarter-cycle was either significantly or marginally shortened (9.81→13.69: 136.6 ± 16.3 ms to 126.7 ± 19.5 ms, $p = .09$; 6.56→9.81: 153.8 ± 18.4 ms to 134.1 ± 17.1 ms; $p < .0001$). Conversely, with large decreases in *g* that called for increases in racket period, the last quarter-cycle increased in length, although this increase was only marginally significant (9.81→8.10: 132.2 ± 20.5 ms to 141.9 ± 16.7 ms, $p = .08$; 13.69→9.81: 112.3 ± 15.3 ms to 118.2 ± 15.3 ms, $p = .08$). It is therefore a possibility that participants started adjusting the upward decelerative phase of racket motion on the next quarter-cycle after the transition, within 150–200 ms. This in turn would suggest that information in the ball's descent, such as gap closure, begins to influence racket motion.

Correlations between informational variables and racket oscillation. To assess the information hypotheses, we performed correlations between ball variables near the transition and racket variables on the three succeeding cycles (C_0, C_1, C_2). The results for Session G appear in Table 4. Considering the control of racket period, the highest correlations are with the ball's flight period in the same cycle. Specifically, for stabilizing transitions (decreases in *g*, Table 4a), the durations of the ball's half-periods after the transition (t_{up1} and t_{down1}) are strongly correlated with the C_1 racket period ($R = .91$ and .81). In contrast, correlations with the ball's peak height (h_{p1}) and launch velocity (v_{b1}) after the transition are lower ($R = .65$ and .30, respectively). These findings indicate that the ball's ascending half-period and descending gap closure modulate racket period in the concurrent cycle, *even when the system is within the passively stable region.*

The pattern is similar for destabilizing transitions (increases in *g*, Table 4b), although the correlations are not quite as high. Following the transition, the duration of the ball's half-periods (t_{up1} and t_{down1}) are correlated with the C_1 racket period ($R = .61$ and .88), whereas the ball's peak launch velocity (v_{b1}) has a much lower correlation ($R = .26$); in this case, the correlation with height (Peak Height_1) is higher than before ($R = .77$). This is consistent with the use of ascending half-period, descending gap closure, and perhaps peak height, to adjust racket period in the same cycle. Finally, correlations between ball variables and racket amplitude are all quite low, as observed in Experiment 1.

The results for Session A appear in Table 5, when the transition in α did not dissociate informational variables. As in Experiment 1, it is apparent that racket period following the transition is highly correlated with the ball's upward and downward motion in the concurrent cycle (t_{up0} and t_{down0}). This is the case for stabilizing transitions (increases in α, Table 5a) ($R = .90$ and .95) as well as transitions that were neutral or stabilizing (decreases in α, Table 5b) ($R = .78$ and .90). However, because information was not dissociated, the correlations with h_{p0} and v_{b0} were also high.

In sum, the results indicate that racket period is actively controlled using information from the ball's upward half-period and downward gap closure within the current cycle. Moreover, this information is used to rapidly adjust racket period whether or not the transitions are stabilizing, destabilizing, or neutral.

Discussion

The results of Experiment 2 reinforce and extend those of the Experiment 1. First, following a transition, participants begin to adjust racket motion within one cycle. It even appears that a change in *g* may start to modulate the racket upswing in the next quarter-cycle, with a latency of only 150–200 ms. Importantly, we observe similarly rapid adjustments after stabilizing (and neutral) transitions as we do after destabilizing transitions. This result clearly contradicts hybrid control, in which active stabilization only occurs when the system leaves the passively stable region. On the other hand, it supports mixed control, in which racket oscillation is perceptually regulated on every cycle, but serves to keep bouncing in or near the passively stable region.

Table 4
Correlations Between Ball Variables and Racket Variables in Experiment 2, Session G, for Three Racket Cycles Following a Decrease in G (Table 4A) or an Increase in G (Table 4B)

	Decrease in g (stabilizing) in Session G (13.69→9.81, 11.66→9.81, 9.81→8.10, 9.81→6.56)					
	Racket cycle period			Racket cycle amplitude		
A	C_0	C_1	C_2	C_0	C_1	C_2
Ball variables						
Up_0 half-period (t_{up0})	0.94	0.37	0.35	0.24	0.03 (ns)	0.08 (ns)
$Down_0$ half-period (t_{down0})	0.89	0.39	0.37	0.17	0.08 (ns)	0.09 (ns)
Up_1 half-period (t_{up1})	0.29	0.91	0.40	0.30	0.12 (ns)	0.04 (ns)
$Down_1$ half-period (t_{down1})	0.28	0.81	0.30	0.25	−0.06 (ns)	−0.03 (ns)
Peak $height_1$ (h_{p1})	−0.03 (ns)	0.65	0.05 (ns)	0.37	0.11	0.03
Launch $velocity_1$ (v_{b1})	−0.20	0.30	−0.16	0.25	0.06 (ns)	−0.03 (ns)
N			234			

	Increase in g (destabilizing) in Session G (6.56→9.81, 8.10→9.81, 9.81→11.66, 9.81→13.69)					
	Racket cycle period			Racket cycle amplitude		
B	C_0	C_1	C_2	C_0	C_1	C_2
Ball variables						
Up_0 half-period (t_{up0})	0.84	0.25	0.36	0.24	0.02 (ns)	0.17
$Down_0$ half-period (t_{down0})	0.86	0.41	0.52	0.16	0.01 (ns)	0.17
Up_1 half-period (t_{up1})	0.48	0.61	0.62	−0.14	−0.10 (ns)	−0.09 (ns)
$Down_1$ half-period (t_{down1})	0.29	0.88	0.58	0.31	0.32	0.33
Peak $height_1$ (h_{p1})	−0.13 (ns)	0.77	0.35	0.27	0.36	0.21
Launch $velocity_1$ (v_{b1})	−0.40	0.26	−0.22	0.38	0.39	0.19
N			234			

Note. Unless indicated otherwise (ns), all correlations are significant ($p < .05$). N = Number of studied cycles; C_0 = cycle that immediately follows the key event; C_1, C_2 = subsequent cycles.

Second, the visual information used to modulate racket period appears to be the duration of the upward half-period of the ball's trajectory in the same cycle, rather than the ball's launch velocity or peak height. This observation depends on the fact that informational variables were dissociated by varying g between or within trials. The finding that the downward half-period is also strongly correlated with racket period could merely be a consequence of the necessary correlation between the two half-periods of the ball's flight. However, when g was perturbed at the peak of flight, the quarter-cycle analysis suggested that the ball's descent can influence the racket upswing in the next quarter-cycle, consistent with reliance on the rate of gap closure to fine-tune racket period. The only anomaly appeared after destabilizing transitions that increased g, when the correlation for peak height (.77) was in between those for upward half-period (.61) and downward half-period (.88). This pattern suggests that the sudden drop in ball height was more salient than the shortening of upward half-period, and participants sought to correct by relying more on the downward gap closure. Note that post-transition errors also undershot the target (Figure 7b) and impact acceleration was positive (Figure 6b) in these conditions, indicating that impact occurred too early in the upswing when the impact velocity was too low.

Adaptive adjustments in racket period occurred very rapidly after a g transition, within one cycle, making it unlikely that participants learned the new value of g. This is supported by the observation that accurate bouncing was, on average, recovered as quickly (if not faster) following g transitions as α transitions, after only two and three bounces, respectively. This strongly implies that high correlations between the ball's flight period and racket period were indeed due to modulation by flight period, rather than by peak height or launch velocity corrected by an implicitly learned value of g.

Finally, the data are consistent with the finding in Experiment 1 that the period and amplitude of racket oscillation can be regulated independently, implying separate control parameters. Specifically, a change in g elicits a permanent change in period and a transient change in amplitude, in the same direction; whereas conversely, a change in α elicits a permanent change in amplitude and a transient change in period, in opposite directions. Moreover, adjustments in racket period seem to take priority over racket amplitude. In Session A, the transient adjustment in period actually occurred a cycle before the more gradual shift in amplitude.

General Discussion

The purpose of the present study was to address a central question about the nature of perception and action: to what extent can the organization of behavior be attributed to physical and informational constraints? The ball bouncing task is a useful model system with which to investigate this problem, because its stability properties and the available information can be theoretically analyzed and experimentally manipulated. In this article we examined three issues: (a) the contributions of passive and active stabilization to the control of behavior, (b) the visual information used for

Table 5
Correlations Between Ball Variables and Racket Variables in Experiment 2, Session A, for Three Racket Cycles Following an Increase in α (Table 4A) or a Decrease in α (Table 4B)

	Increase in a (stabilizing) in Session A (0.41→0.48, 0.45→0.48, 0.48→0.52, 0.48→0.55)					
	Racket cycle period			Racket cycle amplitude		
A	C_0	C_1	C_2	C_0	C_1	C_2
Ball variables						
Up_0 half-period (t_{up0})	0.90	0.63	0.41	0.03 (ns)	−0.15	−0.09 (ns)
$Down_0$ half-period (t_{down0})	0.95	0.66	0.44	0.02 (ns)	−0.13	−0.07 (ns)
Up_1 half-period (t_{up1})	0.58	0.88	0.46	0.15	−0.02 (ns)	−0.07 (ns)
$Down_1$ half-period (t_{down1})	0.64	0.95	0.47	0.14	−0.07 (ns)	−0.09 (ns)
Peak $height_0$ (h_{p0})	0.78	0.47	0.27	−0.00 (ns)	−0.17	−0.11 (ns)
Peak $height_1$ (h_{p1})	0.36	0.78	0.29	0.14	−0.06 (ns)	−0.13 (ns)
Launch $velocity_0$ (v_{b0})	0.90	0.63	0.42	0.03 (ns)	−0.14	−0.09 (ns)
Launch $velocity_1$ (v_{b1})	0.59	0.89	0.46	0.14	−0.02 (ns)	−0.08 (ns)
N				234		

	Decrease in a (neutral) in Session A (0.55→0.48, 0.42→0.48, 0.48→0.45, 0.48→0.41)					
	Racket cycle period			Racket cycle amplitude		
B	C_0	C_1	C_2	C_0	C_1	C_2
Ball variables						
Up_0 half-period (t_{up0})	0.78	0.47	0.35	0.25	0.18	0.13 (ns)
$Down_0$ half-period (t_{down0})	0.90	0.40	0.34	0.32	0.28	0.21
Up_1 half-period (t_{up1})	0.37	0.87	0.37	0.24	0.34	0.10 (ns)
$Down_1$ half-period (t_{down1})	0.45	0.94	0.34	0.21	0.27	0.07 (ns)
Peak $height_0$ (h_{p0})	0.63	0.21	0.13 (ns)	0.14	0.04 (ns)	0.02 (ns)
Peak $height_1$ (h_{p1})	0.16	0.79	0.20	0.12 (ns)	0.16	−0.05 (ns)
Launch $velocity_0$ (v_{b0})	0.78	0.47	0.36	0.25	0.18	0.12 (ns)
Launch $velocity_1$ (v_{b1})	0.37	0.88	0.37	0.23	0.34	0.10 (ns)
N				234		

Note. Unless indicated otherwise (not significant [ns]), all correlations are significant ($p < .05$). *N* = Number of studied cycles; C_0 = cycle that immediately follows the key event; C_1, C_2 = subsequent cycles.

control, and (c) how it modulates the parameters of action. The results of Experiments 1 and 2 converge on the following conclusions.

Control Mode

First, what mode of control is used to stabilize bouncing? We tested four hypotheses, including passive, active, hybrid, and mixed control. The results consistently point to the mixed control hypothesis, in which racket oscillation is actively regulated on every cycle in order to keep the system in or near the passively stable region.

Contrary to pure passive stabilization, under which no active adjustments should occur, we observed adaptive racket adjustments within one cycle in response to natural variation in the ball's trajectory due to biological noise (Experiment 1), as well as to sudden transitions in *g* and α (Experiment 2). Following a transition, bouncing recovered with complete error compensation after an average of only two to three cycles, much faster than predicted by passive stabilization models (Schaal et al., 1996; Dijkstra et al., 2004). These findings are in agreement with those of de Rugy et al. (2003) and Wei et al. (2007), who also reported active racket adjustments within one cycle and relaxation times of 2−3 cycles following perturbations of α.

Contrary to the hybrid control hypothesis, under which active adjustments should occur only when the system leaves the passively stable region, we observed such adjustments after both stabilizing and destabilizing transitions. Specifically, racket period was adjusted on the first complete cycle following a *g* or α transition—whether they took the system into or out of the stable region. This is consistent with Wei et al.'s (2007) observation that racket adjustments are proportional to the magnitude of a perturbation whether or not it crossed the stability boundary.

Finally, the data also militate against pure active control, which is blind to passive stability. In nearly all conditions, we find that mean impact accelerations are negative (Experiment 1), or tend to return toward the negative range following a destabilizing transition (Experiment 2, Figure 6) a preference that is not expected from active control. The results are specifically inconsistent with the mirror algorithm, the main active control model, because this algorithm necessarily predicts positive racket acceleration at impact (Schaal et al., 1996), whereas it was generally negative in the present experiment. In addition, traces of passive stability are manifested in the data, specifically in the correlation between the degree of destabilization and the number of relaxation cycles (Experiment 2, Session G). These findings are in agreement with

Wei et al. (2007), who observed similar effects of perturbation magnitude.

Taken together, our results converge with those of Wei et al. (2007, 2008) to unequivocally support the mixed control hypothesis, a form of active control that exploits passive stability. Racket adjustments occur within one cycle whether transitions are stabilizing or destabilizing, and they tend to keep the system in or near the passively stable region. The advantages of this control mode are threefold: it guides the agent to a stable behavioral organization, reduces the magnitude of active adjustments, and increases the stability of behavior. This interpretation is reinforced by the observation that racket adjustments are proportional to perturbation magnitude (Wei et al., 2007), such that deviations from normal oscillation are only as large as needed. Simultaneously, the relaxation time is significantly shortened, increasing the stability of bouncing. Perhaps most importantly, passive stability identifies a stable task solution during learning and performance. In sum, participants appear to take advantage of both physical stability properties and perceptual information to organize their behavior.

Action Parameters

Second, what parameters of racket motion are regulated during active control of bouncing? We observed that both the period and amplitude of racket oscillation are adaptively adjusted to stabilize bouncing. This implies that they are determined by two separate parameters, which can be controlled independently depending on environmental conditions.

Specifically, the period of oscillation tracks changes in g, so that racket period matches the ball's flight period. This was demonstrated by the findings that racket period varied inversely with g in steady-state bouncing (Experiment 1) and shifted to a new permanent value after a g transition (Experiment 2). Once racket period and phase are set, further control of the bounce height is achieved via racket amplitude. Thus, the amplitude of oscillation tracks changes in α, so that the impact velocity is appropriate to hit a ball of a particular elasticity to the target height. This was demonstrated by the findings that racket amplitude varied inversely with α in steady-state bouncing (Experiment 1), and shifted to a new permanent value after an α transition (Experiment 2). Finally, the data suggest that the control of period takes priority over control of amplitude, for the transient adjustment in period preceded the more gradual permanent shift in amplitude after an α transition. We conclude that the oscillator parameters that determine racket period and amplitude can be controlled independently to satisfy the constraints of a particular task.

This finding has implications for the class of oscillators appropriate for modeling rhythmic movements that are influenced by task constraints. Previous models, which were derived from data on unconstrained movements, exhibited an inverse relationship between pacing frequency and movement amplitude (Kay et al., 1987; Beek et al., 1996). Consequently, oscillator frequency and amplitude were modeled as being coupled and controlled by a single parameter, such as the stiffness coefficient in the hybrid Rayleigh-van der Pol. In the present experiment, by contrast, the ball had to reach a defined target height in a gravitational field, so the amplitude and period of racket motion were strongly constrained. The present data imply that models of constrained movements require at least two control parameters to independently modulate oscillation frequency and amplitude.

Visual Information

Third, what visual information is used to modulate the action parameters of period and amplitude? We examined four hypotheses about information in the ball's trajectory, including its launch velocity, peak height, flight period, and the tau-gap. Each of these variables provides information about the timing of the upcoming impact, which could potentially be used to regulate the period of racket oscillation. When they are dissociated by varying g across or within trials, the data consistently point to reliance on the duration of the half-period of the ball's ascent to control racket period, with fine-tuning by gap closure during the ball's descent.

Contrary to the launch velocity hypothesis, the ball's upward velocity after impact is poorly correlated with racket period. During steady-state bouncing (Experiment 1, Session G), the relation is actually negative ($r = -.46$) due to the variation in g across trials. Following a g transition at the peak of flight (Experiment 2, Session G), the correlation within the first complete cycle (C_1) is only .30 after stabilizing transitions, and .26 after destabilizing transitions. These results indicate that participants do not use the ball's launch velocity to regulate racket period.

Contrary to the peak height hypothesis, the apogee of the ball's trajectory is not strongly correlated with racket period. During steady-state bouncing, the correlation coefficient is only .43 (Experiment 1, Session G). In the first full cycle following a g transition (Experiment 2, Session G), it is .65 for stabilizing transitions and .77 for destabilizing transitions. These results imply that participants do not generally rely on peak height to modulate racket period.

In contrast, the duration of the upward half-period of the ball's trajectory is more highly correlated with racket period. In Experiment 1 (Session G) the correlation on the same cycle is .97, and in Experiment 2 (Session G) the correlation after stabilizing g transitions is .91, although it declines to .61 after destabilizing transitions. This pattern of results indicates that the ball's ascending half-period is generally used to modulate racket period, presumably after the ball has reached its peak so the half-period duration is visually specified. The only inconsistency occurs with destabilizing g transitions, when racket period is better correlated with the sudden drop in ball height (.77), leading to greater errors.

In addition, the ball's downward half-period also influences racket period. In Experiment 1 (Session G) the correlation on the same cycle is .94, and in Experiment 2 (Session G) the correlation is .81 after stabilizing transitions and .88 after destabilizing transitions. Moreover, in some conditions the descent of the ball appears to influence the upswing of the racket in the next quarter-cycle. This suggests that the tau-gap or a related variable is also used to fine-tune the racket period.

On the other hand, the present results do not reveal a simple variable used to modulate racket amplitude. Given that racket period is matched to flight period and the phase of impact is approximately constant, the height of bouncing is determined by the amplitude of racket oscillation. Thus, it was somewhat surprising to find that the correlation between error to the target and subsequent racket amplitude was near zero, both during steady-state bouncing (Experiment 1, Session A) and following α transitions (Experiment 2, Session A), when g was constant. This result implies that adjustments in racket amplitude are not based on the error in a single bounce, but may adapt more gradually based on average error over several preceding bounces. Such an interpretation is consistent with the gradual shift in racket amplitude over about four cycles we observed following α transitions (Figure 9b). Given the level of biological noise in bouncing, this would avoid amplifying variable error while reducing constant error with balls of different elasticity.

In sum, when informational variables are dissociated by varying g, racket period is more strongly correlated with the ascending half-period of the ball's flight, rather than its launch velocity or peak height. This is an elegant solution that simply maps the ball's upward half-period into the racket period, a relation that holds independent of the gravitational constant and thus does not require knowledge of g. It also explains why our participants were able to adapt to sudden changes in g within a few cycles, whereas McIntyre et al.'s (2001) astronauts failed to do so after many trials. In our bouncing task, participants had access to upward half-period information that specified the required racket period without knowledge of g, whereas in their catching task the upward half-period information was unavailable, so action had to be recalibrated to a new value of g.

Putting these pieces together, the following account of the perception–action cycle in ball bouncing emerges. The bouncing task involves coupling a limit-cycle racket oscillation to a periodic ball trajectory. The physical coupling at impact yields the bouncing ball map with its passive stability properties. The informational coupling actively stabilizes bouncing cycle by cycle, while keeping the system near the passively stable region, in a form of mixed control. In particular, the half-period of the ball's upward flight is used to control the period of racket oscillation, perhaps by directly modulating the oscillator's stiffness parameter. In addition, a variable related to average bounce error probably modulates a parameter that independently controls the amplitude of racket oscillation, on a slower time scale. De Rugy et al. (2003) proposed a preliminary version of such a model, which used the ball's launch velocity to reset the period of a neural half-center oscillator. Although this enabled the model to rapidly recover from α perturbations, it would not adapt to changes in g as observed in the present data. Instead, the results suggest using the ball's ascending half-period to regulate a parameter governing the period of the racket oscillator.

Mixed control thus takes advantage of both physical and informational constraints in order to realize a stable and adaptive solution for a behavioral task. On the one hand, it serves to reduce adjustments and simplify control when compared to pure active control, and on the other, it serves to reduce relaxation time and increase stability when compared to pure passive control. Such a mixed control mode may be a general strategy for integrating passive stability with active stabilization in perception−action systems (Warren, 2006). For example, it appears to be manifested in the active control of passive dynamic walking in legged robots (Collins, Ruina, Tedrake, & Wisse, 2005; Tedrake, Zhang, Fong, & Seung, 2004), balance in inverted pendulum systems (Foo, Kelso, & de Guzman, 2000; Schöner, 1991), and tasks such as infant bouncing in a "jolly jumper" (Goldfield, Kay, & Warren, 1993) or juggling a soccer ball (Tlili, Mottet, Bupuy, & Pavis, 2004). In this manner, actors take advantage of both physical stability properties and informational variables in order to achieve stable and adaptive patterns of behavior.

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Appendix A

Haptic Information

Assume that ball mass m_b, coefficient of restitution α, and gravitational acceleration g are constant for given conditions, and that contact with the racket occurs at a constant height (h_c). To control the timing of the next impact, a key desideratum is the period of the ball's flight (T_b) between impacts, or the time of its downward flight from the peak of the trajectory until it returns to the contact height (t_{down}).

By the laws of motion for falling bodies, the ball's *i*th flight is completely determined by its launch velocity (v_i), and the resulting flight period T_i is given by

$$T_i = \frac{2v_i}{g}. \qquad \text{(A1)}$$

Assuming $m_b \gg m_r$, the ball's launch velocity following impact can be determined from its incident velocity prior to impact u_{i-1}, by the change in momentum:

$$\begin{aligned} m_b v_i &= \alpha m_b u_{i-1} + F_i \Delta t_i \\ v_i &= \alpha u_{i-1} + \frac{F_i \Delta t_i}{m_b} \end{aligned} \qquad \text{(A2)}$$

where α is the coefficient of restitution, and F_i is the force and Δt_i the duration of contact; note that the latter constitute the impulse of impact $I = F\Delta t$. Substituting (2) into (1), we get

$$T_i = \frac{2\left(\alpha u_{i-1} + \dfrac{F_i \Delta t_i}{m_b}\right)}{g}. \qquad \text{(A3)}$$

Noting that u_{i-1} is equal to the preceding launch velocity v_{i-1} for the $i - 1$th flight, from (1) we obtain

$$u_{i-1} = v_{i-1} = \frac{gT_{i-1}}{2}. \qquad \text{(A4)}$$

Finally, substituting (4) into (3) allows us to predict the current flight period from the preceding flight period and the impact impulse:

$$T_i = \alpha T_{i-1} + \frac{2F_i \Delta t_i}{g m_b} \qquad \text{(A5)}$$

where α, m_b, and g are constants.

Appendix B

Optical Information

(i) Launch velocity. By the laws of motion, the current velocity of a falling body is

$$v = v_o - gt \qquad \text{(B1)}$$

Hence, on the ball's *i*th flight its incident velocity at contact with the racket (u_i) is related to the downward flight time (t_{down}) from the peak height (where $v_o = 0$) to the contact height,

$$u_i = -g t_{down} \qquad \text{(B2)}$$

and rearranging,

$$t_{down} = -\frac{u_i}{g}. \qquad \text{(B3)}$$

Given that the incident velocity is equal to the launch velocity on that cycle ($u_i = -v_i$) and substituting into B3, we obtain that the downward flight time is a function of the launch velocity:

$$t_{down} = \frac{v_i}{g} \qquad \text{(B4)}$$

or

$$T_b = \frac{2v_b}{g}. \qquad \text{(B5)}$$

(ii) Peak height. By the laws of motion, the current height of a falling body is

(*Appendices continue*)

$$h_p - h_c = v_o t - \frac{1}{2} g t_{down}^2 \quad \text{(B6)}$$

Since $v_o = 0$ at the peak height h_p, rearranging we obtain that the downward flight time is a function of peak height:

$$t_{down} = \sqrt{\frac{2h_p}{g}} \quad \text{(B7)}$$

or

$$T_b = 2\sqrt{\frac{2h_p}{g}}. \quad \text{(B8)}$$

(iii) Half-period. The duration of the upward half-period from contact to the peak of the flight (t_{up}) is equal to that of the downward half-period from peak to the next contact (t_{down}). Thus, the downward flight time is specified by the upward half-period:

$$t_{down} = t_{up} \quad \text{(B9)}$$

or

$$T_b = 2t_{up}. \quad \text{(B10)}$$

(iv) Tau-gap. Hitting the ball entails controlling the motion-gap between the ball and the racket. Lee (1976) suggests that time underlies the process of change of any motion-gap with the tau function. Tau of a motion-gap is numerically equal to the ratio of the current size, x of the motion-gap to its current rate of closure $\dot{x}$, i.e.:

$$\tau_c \approx x/\dot{x}. \quad \text{(B11)}$$

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