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Pattern Stability and Error Correction During In-Phase and Antiphase Four-Ball Juggling

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ABSTRACT. The authors studied pattern stability and error correction during in-phase and antiphase 4-ball fountain juggling. To obtain ball trajectories, they made and digitized high-speed film recordings of 4 highly skilled participants juggling at 3 different heights (and thus different frequencies). From those ball trajectories, the authors determined and analyzed critical events (i.e., toss, zenith, catch, and toss onset) in terms of variability of point estimates of relative phase and temporal correlations. Contrary to common findings on basic instances of rhythmic interlimb coordination, in-phase and antiphase patterns were equally variable (i.e., stable). Consistent with previous findings, however, pattern stability decreased with increasing frequency. In contrast to previous results for 3-ball cascade juggling, negative lag-one correlations for catch–catch intervals were absent, but the authors obtained evidence for error corrections between catches and toss onsets. That finding may have reflected participants' high skill level, which yielded smaller errors that allowed for corrections later in the hand cycle.

Keywords: bimanual coordination, coordinative stability, perception–action coupling, timing

A considerable part of the human action repertoire is rhythmic in nature and requires intricate coordination. Walking, breathing, and chewing are common examples. Rhythmic coordination has been studied extensively in the context of interlimb coordination tasks and so-called perception–action tasks involving the coordination between a single-limb movement and an external stimulus (e.g., tones, flashes).

Researchers have observed several behavioral properties across a wide range of instances of rhythmic coordination. The commonality of those properties suggests that generic coordination principles may be at work (e.g., Kelso, 1995; Turvey, 1990). For instance, without special training, people can typically perform only two coordination patterns in

a stable manner (e.g., Yamanishi, Kawato, & Suzuki, 1979; Zanone & Kelso, 1992): *in-phase coordination* (originally defined as simultaneous activation of homologous muscles) and *antiphase coordination* (alternating activation of homologous muscles). In general, in-phase coordination is more stable than antiphase coordination (e.g., Amazeen, Sternad, & Turvey, 1996; Baldissera, Cavallari, & Civaschi, 1982; Cohen, 1971; Kelso, 1995). The differential stability is particularly evident when an antiphase pattern is performed at a gradually increasing tempo or movement frequency. The increase in tempo may induce a loss of stability of antiphase coordination, followed by a spontaneous transition to an in-phase pattern (e.g., Byblow, Carson, & Goodman, 1994; Haken, Kelso, & Bunz, 1985; Kelso, 1981, 1984). Although researchers have found that such coordination principles generalize to both between-person and visuomotor coordination (e.g., Byblow, Chua, & Goodman, 1995; Schmidt, Carello, & Turvey, 1990; Wimmers, Beek, & van Wieringen, 1992), it is by now widely recognized that many and rather diverse (e.g., cognitive, perceptual, neuromuscular, and mechanical) factors may influence the stability features of rhythmic movement (see, e.g., Carson, 2005; Mechsner, Kerzel, Knoblich, & Prinz, 2001; Swinnen, 2002; Swinnen, Heuer, Massion, & Casaer, 1994).

An important caveat in the generalization of the identified coordination phenomena is that they were largely, if not exclusively, found in studies on rhythmic coordination involving rather constrained (e.g., single-joint) movements. The researchers defined the task goals for those movements

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solely in terms of whether they produced a particular coordination pattern in the absence of extensive informational and mechanical interactions with the environment (e.g., Beek, Rikkert, & van Wieringen, 1996; Byblow et al., 1994; Kelso, 1984). In contrast, in real-life activities the required bimanual coordination is often implicit to the task rather than explicitly imposed as is usually the case for laboratory tasks. That difference may have consequences for stability features of bimanual coordination. In this study, our primary aim was therefore to examine to what extent the identified principles generalize to real-life activities involving multiple degrees of freedom that individuals coordinate to achieve a particular, externally defined, task goal or movement outcome (e.g., a sound sequence in drumming or a pattern of ball motions in juggling).

In that context, juggling is a particularly interesting activity because it generally involves relatively unconstrained multijoint limb movements that performers must coordinate with each other to produce a particular pattern of ball motions. For a first pass, we define juggling as keeping a certain number of objects (e.g., balls) aloft by tossing and catching them repeatedly with fewer end-effectors (e.g., hands) than objects, with the proviso that a given hand may never contain more than one ball. As a consequence of that definition, the juggler must empty a hand containing an object in time to catch the next object on its arrival. The juggler can best achieve that objective by throwing and catching objects at regular intervals and by moving the hands in relatively fixed phase relations—that is, in a rhythmic, (quasi-)phase-locked fashion. Although many juggling patterns (defined in terms of toss and catch locations) are possible, two patterns prevail because of their temporal and spatial symmetry and correspondingly low risk of midair collision (see Figure 1): (a) the cascade for an odd number of balls (i.e., a pattern in which the balls are thrown from one hand to the other, resulting in a rotated figure-eight pattern of ball motion) and (b) the fountain for an even number of balls (i.e., a pattern in which the balls are thrown and tossed with the same hand, resulting in two separate circular patterns or columns).

In his well-known juggling theorem, Shannon (1993) formalized the temporal constraint on juggling that is implicit in the aforementioned definition. He posited that, on average, the ratio of the ball-cycle times (holding times plus flight times) over the hand-cycle times (holding times plus hand-empty times) should equal the ratio of the number of balls over the number of hands because balls and hands move in the same time frame (cf., Beek, 1989; Beek & Lewbel, 1995; Shannon, 1993). The theorem has provided an expedient window into the progress of neophytes learning to cascade juggle (e.g., Haibach, Daniels, & Newell, 2004; Hashizume & Matsuo, 2004; Huys, Daffertshofer, & Beek, 2003, 2004; van Santvoord & Beek, 1994) and into experts' performance in cascade juggling (Beek; Beek & Turvey, 1992; van Santvoord & Beek). Within that context, van Santvoord and Beek also examined the phasing

FIGURE 1. In-phase (bottom left) and antiphase (top and bottom right) juggling patterns for three balls (top; cascade only for antiphase) and four balls (bottom panels). The studied four-ball column patterns were juggled in an outward fashion, meaning that the balls were tossed around the body midline and caught on the side of the body. The events analyzed are indicated for the four-ball antiphase pattern for one hand: toss, zenith, catch, and toss onset.

between hand movements. Cascade juggling is essentially an antiphase pattern, however, because the hands have to toss (and catch) alternately. Therefore, that juggling pattern does permit a comparison of the stability properties of in-phase and antiphase coordination. The four-ball fountain pattern is well suited for that purpose because it can be juggled in both in-phase and antiphase (which most jugglers refer to as *sync* and *async*). Moreover, by varying juggling height, one can readily alter the frequency of juggling to determine its effects on pattern stability.

What could researchers expect from such manipulations? Is it reasonable to assume that the stability properties of interlimb coordination as identified in (often) basic laboratory tasks also apply to fountain juggling? There are some relevant issues to be considered in that context. As we have already mentioned, the goal in juggling is to produce a particular, well-defined pattern of ball motions. Jugglers must structure their hand movements to achieve that goal because the ball motions are the product of the hand movements and depend on hand movement aspects such as timing, position, velocity, and acceleration. By definition, however, stable performance does not require a low variability of all those aspects because their effects on the ball motions are not necessarily isolated

but may covary. In addition, the ballistic nature of the ball flights constrains the use of action-relevant visual information pertaining to the ball motion because the ball is typically caught considerably after the time when it first comes into view. That aspect of the use of visual information may have a bearing on the stability features of juggling because the control of catching is likely to rely on relatively old visual information. Although those considerations make it likely that the stability properties of juggling will differ in certain ways from those of more basic rhythmic interlimb coordination tasks, they provide no compelling *a priori* reason to assume that the stability principles for interlimb coordination will not apply to fountain juggling as well. We therefore hypothesized that the stability of in-phase juggling would be higher than that of antiphase juggling, whereas juggling faster would yield less stable performance.

Because our focus was on coordinative stability, we were also interested in the underlying error-correction mechanisms that are evident in variability and serial correlation measures. Van Santvoord and Beek (1996) found that the variability of ball flight times during three-ball cascade juggling was smaller than that of the holding times, which, in turn, was less than that of the hand-empty times, implying that ball-cycle times are less variable than hand-cycle times. In subsequent studies, investigators found that the temporal variability of the catch exceeded the temporal variability of the toss and that significantly negative lag-one autocorrelations characterize the hands' catch-catch cycle but not their toss-toss cycle (cf. Huys et al., 2003; Post, Daffertshofer, & Beek, 2000), which is reminiscent of the findings of Wing and Kristofferson (1973) for continuous tapping. Those findings on juggling are consistent with the idea that jugglers set up a spatial clock. That is, they create a stable time base of discrete events (a clock) for the hands by accurately tossing the balls to a fixed height (Beek, 1989; Beek & Turvey, 1992; van Santvoord & Beek, 1996). In line with that notion—so it was hypothesized—jugglers correct phasing errors in the ball flights (resulting from inaccurate tosses) directly at the catch. That cannot be the entire story, however. After all, a complete correction of an error in the flight time is inconsistent with an increase in temporal variability between the toss and the catch observed by Post et al. Moreover, Huys et al. observed negative lag-one serial autocorrelations not only in catch locations but also in toss locations, implying that additional error-correction mechanisms are operative at the toss.

To better understand error correction in juggling, in the present study we examined variability and serial correlations not only for intervals related to tosses and catches but also for intervals defined by additional events between catch and toss, that is, toss onset and zenith (see Figure 1), and between relevant subintervals (e.g., toss to zenith [T-Z], zenith to catch [Z-C], catch to toss onset [C-TO], and toss onset to toss [TO-T]). Examination of whether error corrections also predominantly occur at the catches is particularly useful in four-ball fountain juggling because tossing errors

do not transfer between the hands in that juggling pattern, whereas they do in cascade juggling. Unlike cascade juggling, fountain juggling consists of two unimanual tasks. The juggler can therefore make local adjustments of phase without influencing the other hand directly through the subsequent ball flight. Conceivably, the freedom to make phase adjustments may allow for an additional kind of error correction that is not possible in cascade juggling. There is no particular reason for researchers to presuppose that corrections would not occur predominantly at the catch in four-ball juggling, however, because that hypothesis applies to juggling in general.

In sum, we conducted the present experiment to examine the two aforementioned hypotheses. First, we expected in-phase juggling to be more stable than antiphase juggling, whereas we expected pattern stability to decrease with increasing juggling cycle frequency. Second, we expected patterns of timing variability and serial correlations in four-ball juggling to be similar to those that researchers have reported for three-ball juggling, with consistently timed tosses and corrections occurring mainly at the catch.

Method

Participants

Four expert male jugglers (mean age = 33.6 years, range = 26.8–38.8 years) participated in the experiment. All were seasoned jugglers who were capable of juggling five balls for more than 5 min. Two of the participants were right-handed (Oldfield, 1971; laterality quotient > .90); the other 2 showed signs of ambidexterity (laterality quotients = .67 and .64, respectively). All participants had normal or corrected-to-normal vision. They signed an informed consent form before participating, and we paid them a small fee for their services. All procedures in the present experiment fully complied with the ethical guidelines of the American Psychological Association and the Declaration of Helsinki. The Ethics Committee of the Faculty of Human Movement Sciences of the VU University Amsterdam approved the protocol.

Experimental Setup

We used a 16-mm high-speed motion picture camera (DBM 55, Teledyne Camera Systems, Arcadia, CA) running at a frame rate of 64 Hz for data collection. We adjusted the camera (i.e., position, focus) at each recording so that the entire juggling pattern was well in view. A plumb line suspended from the ceiling defined the gravitational vertical. Using four 2000-W stage lamps, we optimized lighting conditions. The participants juggled four white stage balls (diameter = 7.3 cm, mass = 130 g). Two small plastic spheres (fishing floats) suspended above each hand with translucent line indicated the required throwing height.

Procedure

Before the experiment, we determined each participant's elbow height (defined as the distance from the olecranon

to the floor while he stood upright and held his upper arms alongside the torso and his forearms horizontal, with the palms of the hands facing upward) as the reference for defining the required juggling heights (i.e., 0.50, 0.75, and 1.10 m above elbow height). We chose the heights so that the corresponding fall times (i.e., 319 ms, 391 ms, and 473 ms) increased approximately linearly, because we were manipulating the height to induce different juggling frequencies. Participants juggled both the in-phase and antiphase four-ball patterns, with balls being tossed around the body midline and being caught at the side of the body (see Figure 1). Because only 4 jugglers participated, we did not strictly counterbalance the order of presentation of the different conditions. Instead, we varied the order from participant to participant (that procedure seemed appropriate because of the high skill level of the participants). The recording started once participants had achieved a comfortable mode of juggling and involved 5–10 juggling cycles (recording times varied from 4.9 s to 12.0 s, depending on participant and condition). Because of individual variations in holding times, the manipulation of juggling height did not precisely prescribe juggling frequency across participants. Within participants, however, variations in juggling height were reliably associated with variations in juggling frequency.

Preprocessing

After development, we projected the films (Kodak 7251, Ektachrome high-speed daylight film, 400 ASA) onto the grid screen of a film-motion analyzer (NAC type MC OF) by using a 16-mm projector (NAC Type RH 160F) linked to a computer. We adjusted the projector's orientation to align the visible plumb line with the vertical axis of the projection screen. For each frame, we manually placed a transparent sensor over the center of each ball to determine its horizontal and vertical screen coordinates. To minimize digitization noise, we drew a small circle that matched the convex hull of the ball image on the sensor; the circle allowed for accurate positioning of the sensor at the heart of the ball. We recorded the screen coordinates of the ball image in a particular frame by pressing a button on the sensor, on which the next frame was projected. The procedure resulted in four two-dimensional time series (i.e., one for each ball).

Data Analysis

We performed all analyses on a conventional personal computer (Dell Optiplex GX620) by using MatLab Version 6.5 (The MathWorks, Natick, MA). We were able to directly use screen coordinates (as follows) in the analyses because the juggling pattern was performed in a plane perpendicular to the camera direction. We defined the fundamental frequency per ball from the maximum in the y coordinates' power spectral density. We defined *juggling frequency* as mean fundamental frequency of all the balls. For all subsequent analyses, we low-pass filtered the x and

y coordinates of the balls by using a bidirectional fourth-order Butterworth filter (cutoff frequency = 15 Hz). We used the y coordinates to determine the moments of toss (i.e., ball release), zenith, catch, and toss onset per ball (cf. Figure 1). We defined moment of toss and moment of catch as local maxima and minima, respectively, in the time-derivative of the y coordinates. Those extremes were readily discernable because the time derivative changed at a constant rate between those points. We similarly defined moment of zenith and moment of toss onset as the local maxima and minima in the y coordinates between toss and catch (for zenith) and catch and toss (for toss onset), respectively. (Contrary to the denotation of toss onset, we do not wish to imply that that event necessarily is the actual moment when the intentional tossing movement is initiated. Nevertheless, it represents the moment in time when the movement direction reverses, which is a prerequisite for producing the next toss.) We discarded events that occurred within five samples from the beginning and the end of a trial, and we defined the initial toss for each ball as a first event. For asynchronous juggling, we considered the first toss of the preferred hand as the first event; whereas for synchronous juggling, we considered the first toss of the pair of tosses as the first event. We used the timing of the four events (toss, zenith, catch, and toss onset) to calculate the relative phase of the balls with respect to each other (see the Relative Phase section).

Relative Phase

To examine how consistently two balls were juggled per hand, we estimated the relative phase at events associated with balls thrown by the same hand (the within-hand relative phase, RP_{wh} , defined separately for the left and right hands). We similarly assessed the consistency of the between-hand phasing by comparing events of the left hand with the corresponding events of the right hand (yielding the between-hand relative phase, RP_{bh}). Note that we used pointwise estimates of relative phase because researchers have already shown the primary importance of the aforementioned points along the balls' trajectories (e.g., see Post et al., 2000, for a comparison with phase definitions with continuous time dependency).

Our definitions of RP_{wh} and RP_{bh} at the toss moments are illustrated in Figure 2. By inference, we expected a value of π for RP_{wh} , reflecting equally temporally spaced events of the two balls. Notice, however, that if event $i + 1$ consistently occurs too early with respect to event i (yielding a consistent negative deviation from π), then event $i + 2$ must always occur too late relative to event $i + 1$ (yielding a consistent positive deviation from π). To prevent averaging out of such alternating negative and positive deviations, we calculated RP_{wh} only for one ball relative to the other (i.e., the arrows in Figure 2A start only at every second toss). For the same reason, we calculated RP_{bh} only for one hand (left) relative to the other (right). For each of the four events, we formally computed RP_{wh} by using the following equation:

$$RP_{wh}(i) = 2\pi \frac{t(i)}{T(i)}, \quad (1)$$

where $t(i)$ is the interval between two subsequent occurrences of an event (i.e., between events i and $i + 1$), and $T(i)$ denotes the interval between two subsequent occurrences of that event for the same ball. Likewise, we calculated RP_{bh} sequences by using the following equation:

$$RP_{bh}(i) = 2\pi \frac{t^r(i)}{T^r(i)}, \quad (2)$$

where t^r is the interval between the occurrences of the considered event in the right and left hands, and T^r is the interval between two subsequent occurrences of the event for the right hand.

From those phase sequences, we calculated the absolute error for RP_{wh} ($AE_{RP_{wh}}$, i.e., the absolute deviation from the expected values of π) and the constant error for RP_{bh} ($CE_{RP_{bh}}$; i.e., the signed deviation from the expected value, namely, 0 for in-phase juggling and π for antiphase juggling). We used the absolute error for within-hand measures because that measure does not discriminate between leading or lagging hands, whereas the constant error for between-hand measures provides exactly that information. It tells us whether the left hand or the right hand leads (yielding negative or positive values, respectively). We determined the sequences of $AE_{RP_{wh}}$ and $CE_{RP_{bh}}$ by using circular statistics (Batschelet, 1971), and we calculated trial averages and circular variances (s). In the following discussion the terms, $AE_{RP_{wh}}$ and $CE_{RP_{bh}}$ refer to trial averages of the phase sequences. We used the transformed circular variance (TCV_{wh} and TCV_{bh} for within- and between-hand measures, respectively) as the measure of relative phase variability, that is, $TCV = (2s)^{1/2}$.

Temporal Intervals

To gain insight into the error correction underlying performance variability, we focused on interval timing for balls

thrown by the same hand. As has become customary in juggling studies, we first looked at the variability of three intervals: flight time, holding time (time loaded), and hand-empty time (time unloaded). To compare the present variability results with those of previous studies (e.g., van Santvoord & Beek, 1996), we also calculated the corresponding coefficients of variation (CV_T), defined as the standard deviation divided by the mean. We analyzed the variability of ball and hand intervals (i.e., intervals between consecutive occurrences of a particular event either for the same ball or for balls thrown by the same hand, respectively, with toss [T], zenith [Z], catch [C], and toss onset [TO] as the events of interest), by using the standard deviation and the coefficient of variation of between-cycle intervals (SD_{bc} and CV_{bc} , respectively).

For a comparison with the findings of Post et al. (2000) and Huys et al. (2003), we also calculated serial correlations of hand-cycle intervals. The presence of negative serial correlations between two consecutive intervals implies that long (short) intervals tend to precede short (long) intervals. Such an alternation may suggest that jugglers adjust the duration of the second interval to the duration of the first to minimize the variation in the duration of the sum of both intervals. Although Wing and Kristofferson (1973) have argued that negative serial correlations may also be present without such corrections, the intrinsic dependence on visual feedback in juggling suggests that negative serial correlations are the result of temporal corrections in that task. On the other hand, positive correlations occur when long (short) intervals are generally followed by long (short) intervals, suggesting that jugglers are not attempting to minimize the variation in the duration of the sum of both intervals. One should note that the presence of low-frequency modulations (trends and drifts) of the intervals of interest is also a potential source of (more) positive correlations (Madison, 2001). We therefore tested the interval sequences for the presence of trends and drifts by visually inspecting their five-point averages. We calculated the lag-one and lag-two serial

autocorrelations for the hand-cycle intervals of all four events and the serial correlations between intervals of subsequent events (e.g., T-T with Z-Z).

Finally, we considered between-event intervals (i.e., the intervals between consecutive events of the same ball: T→Z→C→TO→T). We analyzed the variability of those between-event intervals (T-Z, Z-C, C-TO, and TO-T) as well as hand-specific serial correlations of those reference intervals with the preceding intervals (of the same ball) ending at the start event of the reference interval (e.g., C-TO with preceding Z-C, T-C, and TO-C). We assessed the variability by using both the standard deviation and the coefficient of variation (SD_{be} and CV_{be} , respectively). We quantified the correlations by using the number of significant positive and negative correlations (as defined in the Statistical Analysis section) summed over participants and conditions and, if informative, partitioned into the levels of the different factors.

Statistical Analysis

We used repeated measures analysis of variance (ANOVA) to evaluate effects of pattern (in-phase and antiphase), height

(0.50, 0.75, and 1.10 m), hand (left and right), part (flight time, holding time, and hand-empty time), cycle (ball and hand cycles), event (T, Z, C, and TO), and interval (T-Z, Z-C, C-TO, and TO-T). For every particular test, we have indicated in the text the subset of factors. We used Huynh-Feldt corrected degrees of freedom (we indicate them where appropriate). We chose a significance level of $\alpha = .05$ in the ANOVAs and serial correlations. We used paired-samples t tests for post hoc comparisons, with a modified Bonferroni adjustment to correct for multiple tests (Sankoh, Huque, & Dubey, 1997). When reporting post hoc comparisons, we indicate the adjusted p level in the text as p^* . Data are presented in the text as M and, in parentheses, SD .

Results

Because of the considerable reduction of the recorded data (in the present analysis, we considered the timing of only four events per ball cycle), we first illustrate here the time series that we obtained in the experiment. The left panels of Figure 3 show a short section of the normalized filtered y coordinates of the four balls for in-phase and

FIGURE 3. Typical time-series of the normalized y -coordinates of the four balls, shown for a portion of the trials (top left panel, in-phase juggling; bottom left panel, antiphase juggling), and corresponding normalized ball trajectories (right panels, x and y coordinates). In the left panels, the events of interest are indicated: Squares represent tosses, diamonds represent zeniths, triangles represent catches, and circles represent toss onsets. Solid and dashed lines are used to visualize the separate balls thrown by each hand.

antiphase juggling of 1 participant at the middle juggling height, with symbols indicating the timing of the events that we considered. The right panel shows the corresponding x - y trajectories.

As expected, the manipulation of juggling height induced different juggling frequencies: 1.20 Hz (0.06 Hz), 0.94 Hz (0.12 Hz), and 0.78 Hz (0.10 Hz) for in-phase juggling and 1.24 Hz (0.11 Hz), 0.98 Hz (0.12 Hz), and 0.78 Hz (0.09 Hz) for antiphase juggling, for the heights of 0.50, 0.75, and 1.10 m, respectively. We confirmed those variations in a Pattern $\times$ Height repeated measures ANOVA on juggling frequency, which showed an effect of height, $F(1.5, 4.6) = 39.7$, $p < .01$, $\eta_p^2 = .93$; all levels differed significantly, $p^* < .049$.

Relative Phasing

Within-Hand Phasing

To ascribe variations in stability across juggling patterns and heights to the just-mentioned factors, we first had to establish that the average performed patterns did not covary. The Hand $\times$ Event $\times$ Pattern $\times$ Height repeated measures ANOVA for AE_{RP_wh} did not show any significant effects. That result paved the way for the use of TCV_{wh} in a straightforward examination of variability. For TCV_{wh} , the ANOVA showed a significant effect of only event, $F(2.4, 7.0) = 9.3$,

$p < .01$, $\eta_p^2 = .76$. The reason for that result was that TCV_{wh} was significantly larger (i.e., less-stable phasing), $p^* < .018$, for the zenith (4.3° [0.8°]) than for the toss onset (4.0° [0.8°]); $TCV_{wh} = 5.5^\circ$ (1.0°) and 4.2° (0.4°) for the catch and the toss, respectively.

Between-Hand Phasing

The Event $\times$ Pattern $\times$ Height repeated measures ANOVA for CE_{RP_bh} showed no significant effects. The ANOVA on TCV_{bh} revealed that the between-hand variability was affected significantly by event, $F(1.6, 4.8) = 67.2$, $p < .001$, $\eta_p^2 = .96$, and by height, $F(1.7, 5.1) = 53.6$, $p < .001$, $\eta_p^2 = .95$. There was an effect of event because TCV_{bh} was significantly higher, $p^* < .019$, at the catch (14.6° [1.4°]) than at the toss (8.8° [1.3°]), the zenith (10.9° [1.9°]), and the toss onset (9.6° [1.9°]); and TCV_{bh} was higher at the zenith than at the toss onset. Post hoc analyses of the effect of height showed that TCV_{bh} was significantly higher (i.e., less stable phasing), $p^* < .030$, for juggling at 0.50 m (13.1° [1.4°]) than for juggling at 0.75 m (10.5° [1.6°]) and for juggling at 1.10 m (9.4° [1.8°]). The effect of pattern was not significant for either within-hand or between-hand relative phasing, indicating that the in-phase and antiphase patterns were equally stable in the present experiment.

Interval Timing

We analyzed the variability of flight times, holding times, and hand-empty times by means of a Hand $\times$ Part $\times$ Pattern $\times$ Height repeated measures ANOVA for CV_T . The analysis revealed a significant effect of part, $F(1.5, 4.4) = 127.7$, $p < .001$, $\eta_p^2 = .98$, and a significant Hand $\times$ Part $\times$ Pattern $\times$ Height interaction, $F(3.5, 10.5) = 5.1$, $p < .05$, $\eta_p^2 = .63$. Post hoc analyses of the part effect revealed that the variabilities of the flight times, holding times, and hand-empty times all differed significantly, $p^* < .027$ (CV_{Ts} were 0.029 [0.003], 0.052 [0.008], and 0.11 [0.010], respectively). Figure 4 shows the average CV_T for the Hand $\times$ Part $\times$ Pattern $\times$ Height interaction, illustrating that the Pattern $\times$ Height interaction differed between hands in the hand-empty intervals.

Between-Cycle Intervals

In this section, we discuss the variability analyses for the between-cycle intervals and the serial correlation analyses of the subset of those intervals related to the hand cycles. The Hand $\times$ Cycle $\times$ Event $\times$ Pattern $\times$ Height repeated measures ANOVA for SD_{bc} revealed significant effects of cycle, $F(1, 3) = 10.3$, $p < .05$, $\eta_p^2 = .77$, and event, $F(3, 9) = 18.2$, $p < .001$, $\eta_p^2 = .86$; a significant Hand $\times$ Event $\times$ Height interaction, $F(6, 18) = 2.7$, $p < .05$, $\eta_p^2 = .48$; and a significant Cycle $\times$ Event $\times$ Height interaction, $F(6, 18) = 4.2$, $p < .01$, $\eta_p^2 = .58$. Post hoc analyses of the effect of cycle indicated that hand cycles were significantly less variable than ball cycles (SD_{bc} s = 19 ms [1 ms] and 21 ms [2 ms], respectively). SD_{bc} was significantly larger, $p^* < .015$, at the catch (24 ms [3 ms]) than at the zenith (19 ms [2 ms]) and at the toss onset (18 ms [2 ms]), whereas SD_{bc} also differed between zenith and toss onset, as was revealed by the post hoc analyses of the effect of event (SD_{bc} = 19 ms [1 ms] for the toss). The Hand $\times$ Event $\times$ Height interaction for SD_{bc} suggested that for a juggling height of 1.10 m, the left hand intervals were more variable than were those of the right hand for the catch, whereas the converse was true for toss onset. None of those differences was significant, however, $p^* > .00004$. The Cycle $\times$ Event $\times$ Height interaction for SD_{bc} similarly suggested that the effect of cycle was particularly strong for juggling at 0.50 m and was also strong for the toss in juggling at 0.75 m. But again, none of the differences was significant, $p^* > .00005$.

The Hand $\times$ Cycle $\times$ Event $\times$ Pattern $\times$ Height repeated measures ANOVA for CV_{bc} showed significant effects of cycle, $F(1, 3) = 247.1$, $p < .01$, $\eta_p^2 = .99$; event, $F(3, 9) = 17.7$, $p < .001$, $\eta_p^2 = .86$; and height, $F(2, 6) = 16.1$, $p < .01$, $\eta_p^2 = .84$; and also showed a significant Cycle $\times$ Event interaction, $F(1.7, 5.8) = 9.2$, $p < .05$, $\eta_p^2 = .76$. Hand cycles were significantly more variable than ball cycles (CV_{bc} s of 0.37 [0.005] and 0.20 [0.003], respectively). The significant effect of event was the result of a significantly higher, $p^* < .030$, variability of C–C intervals (0.035 [0.006]) than Z–Z intervals (0.027 [0.004]) and TO–TO intervals (0.025 [0.004]); whereas the CV_{bc} for T–T intervals (0.027 [0.002])

did not differ significantly from those of the other intervals. Post hoc analyses showed that the CV_{bc} for 0.50 m (0.033 [0.004]) differed significantly, $p^* < .033$, from those of the

FIGURE 5. The lag-one (A), lag-two (B), and cross-event correlation coefficients (C) for the interval sequences of the hand cycle. The values are shown for both hands (left = squares; right = circles) and for all events (toss [T], zenith [Z], catch [C], and toss onset [TO], respectively). Nonsignificant correlation coefficients are indicated in gray and significant correlation coefficients in black. For clarity, the number of significant correlation coefficients (out of a possible 24 cases) is indicated for each hand.

other two juggling heights ($CV_{bcS} = 0.028$ [0.004] and 0.025 [0.004] for the 0.75-m and 1.10-m heights, respectively). Note that the absolute variability of the timing (i.e., SD_{bc}) did not show an effect of height (see the earlier discussion). Post hoc analyses of the Cycle $\times$ Event interaction showed that the effect of cycle was significant for all events, $p^* < .012$, whereas only the difference between the variability of C–C intervals and TO–TO intervals was significant for both hand and ball cycles.

Figure 5 shows the coefficients for the serial correlations that we calculated for hand-cycle intervals; the number of significant positive and negative correlations is also indicated for each hand. As one can see, significant negative lag-one autocorrelations were least common for the T–T intervals and most common for the TO–TO intervals. In

the latter case as well, however, more than two thirds of the correlations were not significant. Figure 5 shows that only very few lag-two correlations were significant (middle panel), whereas the cross-event correlations (i.e., between-hand cycle intervals of subsequent events) were often significantly positive (right panel), particularly for T–T and subsequent Z–Z intervals and for Z–Z and subsequent C–C intervals. We could not discern any trends or drifts in the interval sequences, suggesting that those positive correlations captured an inherent aspect of the performance. The juggler cannot influence the ball trajectory after he tosses the ball until the ball is caught, which means that one should expect a positive correlation between T–T and subsequent Z–Z intervals if the toss is timed very consistently (because of the accumulation of temporal errors). The positive corre-

lation between Z–Z and subsequent C–C intervals suggests that timing errors at the zenith were not consistently corrected at the subsequent catch. The instances of significant positive correlations were evenly distributed across patterns, heights, and participants. We gained a more detailed picture of interval timing from analyses of between-event intervals, which are presented next.

Between-Events Intervals

We analyzed the variability of the between-event intervals SD_{be} and CV_{be} by means of a Hand $\times$ Interval $\times$ Pattern $\times$ Height repeated measures ANOVA. For SD_{be} , the analysis revealed significant effects of interval, $F(3, 9) = 13.3$, $p < .01$, $\eta_p^2 = .82$, and height, $F(2, 6) = 5.9$, $p < .05$, $\eta_p^2 = .66$. Post hoc analyses of the effect of interval showed that the C–TO interval was significantly more variable than the TO–T interval, $p^* < .011$ ($SD_{be} = 14$ ms [1 ms], 12 ms [1 ms], 16 ms [1 ms], and 10 ms [2 ms] for T–Z, Z–C, C–TO, and TO–T intervals, respectively). The between-event intervals were significantly more variable, $p^* < .023$, for juggling at 1.10 m (14 ms [1 ms]) than for juggling at 0.50 m (12 ms [1 ms]); their variability at 0.75 m was 13 ms (1 ms). The ANOVA for CV_{be} also showed significant effects of interval, $F(1.5, 4.6) = 18.6$, $p < .01$, $\eta_p^2 = .86$, and height, $F(2, 6) = 15.4$, $p < .01$, $\eta_p^2 = .84$. CV_{be} was significantly higher, $p^* < .013$, for the C–TO interval (0.071 [0.009]) than for both the T–Z interval (0.039 [0.0002]) and the Z–C interval (0.038 [0.004]). $CV_{be} = 0.082$ (0.021) for the TO–T interval. The effect of height on CV_{be} was in the direction opposite to that obtained for SD_{be} , indicating that CV_{be} was significantly higher, $p^* < .034$, for the lowest juggling height than for the other juggling heights ($CV_{be} = 0.066$ [0.008], 0.055 [0.005], and 0.051 [0.010] for juggling heights of 0.50, 0.75, and 1.10 m), respectively.

Figure 6 shows the serial correlation coefficients for the various between-event intervals. No trends and drifts were discernable in the time series. The analyses showed that negative correlations were most significant with the C–TO interval as reference (third column from the left). The C–TO intervals were significantly negatively correlated with preceding Z–C intervals in nearly half of the cases, and the T–C and TO–C intervals were significantly negatively correlated in about 20% of the cases. There was a strong asymmetry between hands: Most significant negative correlations were present for the right hand (see Figure 6). Significant correlations between T–C and C–TO intervals and between TO–C and C–TO intervals occurred almost twice as often for in-phase (seven and eight cases, respectively) coordination than for antiphase (four cases for each) coordination. Last, the significantly negative correlation between Z–C and C–TO intervals was particularly strong for 1 participant, producing 9 of the 21 significant cases.

Discussion

Juggling is a perceptual-motor task that humans are generally unable to perform without practice. The juggling

task we studied here, four-ball fountain juggling, typically takes several months to master. We examined the stability, timing variability and serial-lag correlations of in-phase and antiphase four-ball column juggling patterns performed at different frequencies (i.e., heights) by highly skilled jugglers with many years of training experience at different frequencies (i.e., heights). We compared performance of this real-life task with that of the finger- and hand-wiggling tasks that researchers typically use to study the stability features of rhythmic bimanual coordination and also with the documented performance of three-ball cascade juggling.

With regard to pattern stability, the results were clear-cut: In-phase and antiphase juggling were equally stable, and faster juggling resulted in greater variability of the relative phasing between the hands. That is, in four-ball fountain juggling we did not observe the differential stability of in-phase and antiphase coordination that researchers have frequently found in more basic tasks, but we did observe the often-found inverse relation between movement frequency and stability. Those findings raise the question of why the differential stability of in-phase and antiphase coordination was not present in four-ball fountain juggling.

Several important aspects set juggling apart from the tasks that researchers typically use to study rhythmic interlimb coordination. The task of juggling—keeping more balls aloft than hands available to do so—is accomplished most easily if the juggler succeeds in generating a smooth ball-circulation pattern. Despite the tight spatiotemporal constraints on juggling (Beek, 1989; Beek & Lewbel, 1995; Shannon, 1993), the juggler can generate such a pattern in a variety of ways. Because the motion of a single ball cannot be adjusted during the airborne phase, the toss serves as the final control point and is crucial for overall pattern stability. The juggler must control six degrees of freedom (position and velocity in three dimensions) and the timing for each toss. One may expect some compensatory variability between those factors and between subsequent tosses of the hands. The intervals between tosses of both hands differ for in-phase and antiphase juggling, potentially influencing the compensations between subsequent tosses of the different hands for those patterns. In some instances, small constant shifts in (one of) those degrees of freedom may stabilize the ball-circulation pattern. For in-phase juggling, for instance, the performer may reduce the chance of collisions by slightly shifting the toss locations away from the body midline. That shift may not be needed for antiphase juggling because in that type of juggling the balls are more evenly distributed in space at all times.

Because jugglers usually stand upright freely, as was the case in the present experiment, they also are free to set up a driving rhythm for both hands to stabilize the ball-cycling pattern. For in-phase juggling, small knee flexion–extension movements may invoke that rhythm, whereas for antiphase juggling, hip or shoulder rotation around a longitudinal axis, or both, seems most likely. Such additional movements may have influenced pattern stability. In a similar vein, Meesen,

Levin, Wenderoth, and Swinnen (2003) reported that an additional rhythmic head movement influenced the stability features of bimanual circle drawing. Like the underconstrained nature of the tosses, the performer can exploit that freedom to modulate the stability of the ball motion pattern because the task goal does not directly relate to the stability of hand movements.

Although expert jugglers such as the present participants can juggle three, and sometimes even four, balls blindly, vision is in general crucially important in juggling and its acquisition (e.g., the authors know of no reported cases of blind people learning to juggle normally). In juggling, visual information about the required adjustments accumulates when the ball is airborne, but the juggler cannot use that information instantaneously because he first must toss and catch other balls. The possibility of pattern adjustments on the basis of visual information thus differs between juggling and commonly studied rhythmic bimanual coordination tasks in which visual information and proprioceptive information are available all the time and may thus be used for online adjustments. Despite that difference, it is interesting to discuss the role of vision during common rhythmic bimanual coordination tasks so that we can illustrate possible ways in which vision could influence pattern stability in general.

Using augmented feedback, several researchers demonstrated that visual feedback can stabilize bimanual coordination (e.g., Bogaerts, Buekers, Zaal, & Swinnen, 2003; Byblow, Chua, Bysouth-Young, & Summers, 1999; Cardoso de Oliveira & Barthelemy, 2005; Mechsner et al., 2001). Those observations are complemented by neurophysiological data showing that vision modulates contralateral corticospinal excitability (cf. Carson, Welsch, & Pamblanco-Valero, 2005) and that distinctly different (sub)cortical areas are involved in rhythmic bimanual coordination when vision is available and when it is not (cf. Debaere, Wenderoth, Sunaerts, van Hecke, & Swinnen, 2003). Despite those influences of visual information, researchers have reported differential stability of in-phase and antiphase coordination both with (e.g., Kelso, 1984; Tomatsu & Ohtsuki, 2005) and without (e.g., Mechsner et al., 2001; Ridderikhoff, Peper, & Beek, 2005) vision of the moving limbs—a finding that downplays a possible effect of vision of the balls on the absence of differential stability between in-phase and antiphase juggling. At the same time, however, one cannot exclude the possibility that the exact nature of the visual information used differs between in-phase and antiphase juggling. Investigators have shown that the stability of visual judgments of relative phase is higher for in-phase than for antiphase motion (e.g., Bingham, Schmidt, & Zaal, 1999; Zaal, Bingham, & Schmidt, 2000). Huys, Williams, and Beek (2005) reported that this differential stability may be related to eye movements because they found that the coupling between gaze and target motion was stronger for in-phase than for antiphase visual patterns. It is unclear whether similar effects are present for juggling, given that expert jugglers often look at a point located in the center of the pattern (i.e., they adopt a so-called gaze through; Huys

& Beek, 2002). The results of Huys et al. (2005) suggested that eye movement patterns may affect the perception of the juggling pattern, which, in turn, could affect the stability of the juggling performance. To examine that possibility, researchers would have to record eye movements during in-phase and antiphase components of four-ball juggling.

Another potential explanation may be found in the training history of the participants. Differential stability of the two coordination patterns may be present at early stages of skill acquisition, but the differences eventually wash out because of the predominance of the antiphase pattern during practice, in the juggling of both odd and even numbers of objects. Practice can substantially modulate pattern stability, as researchers have demonstrated for the training of coordination modes that are not intrinsically stable, such as rhythmical movements of two limbs with a 90° phase difference (e.g., Fontaine, Lee, & Swinnen, 1997; Wenderoth, Bock, & Krohn, 2002; Zanone & Kelso, 1992). Investigators have also shown that training at a predetermined transition frequency may stabilize antiphase coordination (e.g., Jantzen, Fuchs, Mayville, Deecke, & Kelso, 2001; Temprado, Monno, Zanone, & Kelso, 2002). Because the present experiment involved expert jugglers, it is not unlikely that their extensive antiphase training eliminated previous stability differences between in-phase and antiphase juggling. One could test that suggestion by comparing coordinative stability of four-ball juggling over various skill levels.

Three- Versus Four-Ball Juggling

Following the research of Beek (1989), several researchers have examined the spatiotemporal organization of three-ball cascade juggling (Beek & Turvey, 1992; Haibach et al., 2004; Hashizume & Matsuo, 2004; Huys et al., 2003, 2004; Post et al., 2000; van Santvoord & Beek, 1994, 1996). In contrast, four-ball juggling has received very little or no attention. To our knowledge, the present study is the first in-depth investigation of (four-ball) column juggling. It is interesting to discuss similarities and differences in the performance of three- and four-ball juggling. Van Santvoord and Beek (1996) observed for three-ball cascade juggling that hand-cycle times were consistently more variable than ball-cycle times. The results of the present study corroborated those observations for four-ball juggling. The observed difference in variability of hand-cycle times and ball-cycle times, in combination with the higher spatial variability of the catch than the toss locations, led van Santvoord and Beek to suggest that jugglers try to toss at consistent intervals to a consistent height and that they correct errors directly at the catch. Post et al. (2000) and Huys et al. (2003) found additional support for that suggestion: They reported significantly negative lag-one autocorrelations for C–C intervals of both hands but not for Z–Z and T–T intervals. We failed to replicate that finding and found several indications that our expert four-ball jugglers did not predominantly adapt the timing of the catch to variations in

the toss characteristics but instead made such corrections after the catch. We discuss that issue next.

The variability of both between-hand relative phase and between-cycle intervals was largest at the catch and smallest at the toss onset, whereas the C-TO interval was the most variable between-event interval. Those findings suggest that participants adapted the C-TO interval in response to variations in the moment of catch. One can draw similar conclusions from the serial correlations: There were more significant negative lag-one autocorrelations for the C-C than for the T-T intervals (12 and 7, respectively), whereas the Z-Z and TO-TO intervals also showed significant lag-one autocorrelations (10 and 13, respectively). Moreover, there were significant positive correlations between the T-T and Z-Z intervals and, in many more cases, between the Z-Z and the C-C intervals. Those results argue against a pivotal role of the catch in error corrections, which would have led primarily to significant negative lag-one autocorrelations for C-C intervals and to negative instead of positive correlations between Z-Z and C-C intervals. The additional analyses of the serial correlations of between-event intervals, which were motivated from our need to zoom in on corrections during the holding time, indeed suggested that the jugglers postponed the corrections until after the catch: The C-TO interval was the only interval in which we observed significant negative correlations with the preceding sections of the TO-TO cycle (i.e., the Z-C, T-C, and TO-C intervals). Thus, although the average performances (i.e., between-cycle variability, ball-cycle variability, and hand-cycle variability) of three- and four-ball juggling are similar, the corrections underlying the stable performance appear to differ between the two forms of juggling.

Are there differences between the three- and four-ball juggling patterns that would promote later corrections (i.e., not at, but after, the catch)? In three-ball cascade juggling, balls evidently cross over from hand to hand, whereas in four-ball fountain juggling, they do not (see Figure 1). As we argued in the introduction, that difference implies that fountain juggling may involve more freedom for variations in the phasing between the hands, possibly to correct the pattern. Because smoothness of the ball motion patterns depends not only on the timing of the tosses but also on their locations and velocities, such corrections do not necessarily have to appear in the analyses of interval timing to which we limited the present analyses. In addition, the spatiotemporal aspects of the ball patterns necessarily differ because the balls do not cross over between the hands. Most likely, the widths of both the hand cycles and the ball trajectories are smaller for fountain juggling than for cascade juggling, resulting in a shorter time between toss and catch for fountain juggling. We confirmed that supposition by comparing the average hand-empty interval in the present study (0.16 s; not reported in the Results section) with that reported by van Santvoord and Beek (1996) for three-ball cascade juggling (0.27 s; extracted from their Table 5 and averaged for juggling heights similar to those we used

here for expert jugglers). If less time is available between toss and catch, then a full corrective movement may not be possible, potentially promoting a later correction during the longer C-TO interval (0.24 s; not reported in our Results section).

Another potential reason for the delayed corrections may be found in the fact that both Post et al. (2000) and Huys et al. (2003) studied jugglers of intermediate skill who could not juggle more than three balls, whereas in the present work we studied top-level jugglers with very consistent performance. Our participants achieved consistent performance by making accurate tosses (to appreciate that finding, cf. the ball trajectories depicted in our Figure 5 and those in Figure 2 of Post et al., 2000). The higher consistency may have promoted a later correction (viz. after the catch), as we explain next.

Juggling requires producing a stable ball-circulation pattern, which is highly dependent on accurate tosses. The emphasis on accurate tosses may have been even stronger in the present experiment because of the use of height indicators (which Post et al., 2000, did not use). Although Beek (1989) identified the toss as an anchor point in the juggling cycle (for empirical support, see Post et al., 2000; van Santvoord & Beek, 1996), the results of the present study suggest a slightly different picture because of the consideration of the additional toss onset event. The absence of differential temporal variability between toss onset and toss and the primacy of corrections between catch and toss onset in the present study suggest that the toss was not a temporal anchor point. It seems that the whole act of tossing (from toss onset to actual toss), at least for expert jugglers, is timed so consistently that the whole toss could be more appropriately considered a temporal anchor for juggling.

A stable hand-circulation pattern can promote a stable ball-circulation pattern. Temporal error corrections at the catch would increase the spatial variability of the catch location (cf. van Santvoord & Beek, 1996), thereby necessarily also increasing the variability of the hand trajectory between toss and catch. One can imagine that jugglers can control the toss characteristics best if their hand trajectory is very consistent both before and after the toss. Postponing corrections until after the catch may yield a more stable hand trajectory between toss and catch, thereby enhancing the toss accuracy (and thus the stability of the juggling pattern). The corrections should not influence the subsequent toss, suggesting that jugglers should complete them before the next tossing movement. The present results suggest that the jugglers corrected all timing errors before toss onset. Jugglers evidently may postpone corrections only if they can catch the balls without corrections—in other words if the balls are tossed accurately enough—which typically requires a rather high skill level.

In sum, we discerned what are essentially two (not mutually exclusive) explanations for the apparent differences in error-correction mechanisms between three-ball cascade juggling and four-ball fountain juggling. First, specific

spatiotemporal differences resulting in a shorter toss–catch interval in four-ball fountain juggling may have precluded a complete correction at the catch, thereby promoting a later correction. Second, the high skill level of our participants may have promoted a later correction to further improve the stability of the hand circulation (and, through that, the stability of the ball circulation). Researchers must conduct further studies of the timing patterns of beginning and expert three- and four-ball jugglers to examine those possibilities.

Conclusions

In the present study, we unexpectedly found that in-phase and antiphase coordination are equally stable in expert jugglers who are performing four-ball juggling patterns. As expected, however, juggling at a low frequency tended to be more stable than juggling at a high frequency. We discussed several possible explanations for the unexpected finding, such as conjoint variations in the timing, location, and velocity of the tosses; the use of driving oscillations of other parts of the body; and the unconstrained nature of eye movements. Moreover, we underscored that our highly skilled participants had practiced the antiphase juggling pattern much more often than the in-phase pattern, thereby potentially obscuring an intrinsic differential stability between in-phase and antiphase four-ball juggling. As it stands, however, none of those explanations can be considered definite, and more examinations of their contributions are needed.

In contrast to three-ball cascade juggling, in which corrections reportedly occur primarily at the catch, the corrections in four-ball column juggling occurred predominantly right after the catch in this study. That finding may reflect an actual difference in the spatiotemporal characteristics of three- and four-ball juggling. An alternative explanation is that the high tossing accuracy of the skilled participants in the present study may have promoted corrections later in the movement cycle.

The results of the present study of four-ball juggling were evidently contingent on the very consistent performance of our highly skilled participants. Expert jugglers make optimal use of the perceptual information about task performance. That information mainly comes from vision of the balls, but it also arises from the arm and hand movements (i.e., jugglers may use the details of the tossing movements to predict the ball trajectory). Some researchers have argued that acquiring expertise in juggling principally means improving the integration of all those forms of information. As we argued in the introduction, the integration may even reach the stage in which jugglers can control the balls (i.e., juggle) in absence of any of vision (e.g., blind juggling), which implies that jugglers somehow know the motion of the balls after their release from the available kinesthetic and haptic information, probably on the basis of some kind of internal representation. How jugglers control ball motion is an interesting issue because that skill combines aspects of interception, rhythmic coordination, and

physical manipulation of objects. Studies of (the learning processes underlying) those aspects will be instrumental in further uncovering the control processes underpinning the skill of juggling.

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Biographies of the Editors of the *Journal of Motor Behavior*

RICHARD G. CARSON spent his youth in Northern Ireland. He received his undergraduate degree in psychology at the University of Bristol. Thereafter he did graduate research at Simon Fraser University in Vancouver, Canada. He held a number of research fellowships at the University of Queensland in Brisbane, Australia, where he was appointed to a research professorship in 2002. At the beginning of 2006, he returned to Ireland to serve as professor at Queen's University Belfast. His research focuses on neural plasticity—that is, the capacity of the central nervous system to adapt in a manner that generates new functional capabilities or restores functional capabilities that have been lost, for example, because of brain injury or aging. He has served as an Executive Editor of the *Journal of Motor Behavior* since 2005.

ROBERT L. SAINBURG did his undergraduate work at New York University, where he received a baccalaureate in occupational therapy and subsequently practiced in clinical neurorehabilitation. He received his master's degree in physiology and neurobiology and his doctorate in neuroscience from Rutgers University. He then did post-doctoral research under the mentorship of Claude Ghez in the Department of Neurobiology at Columbia University in New York. He is now an associate professor of kinesiology and neurology at The Pennsylvania State University. In his research Dr. Sainburg integrates biomechanical with neurobiological principles to elucidate the neural processes underlying the planning and execution of multijoint movements and bilateral coordination and to describe the mechanisms underlying coordination deficits. His research program is ultimately directed toward effecting improvements in clinical rehabilitation. He has served as Executive Editor of the *Journal of Motor Behavior* since 2007.

DAGMAR STERNAD is a full professor at the Department of Kinesiology and the Integrative Bioscience Program at the Pennsylvania State University. Following her undergraduate work at the Technical University of Munich, Germany, she received her master's and doctoral degrees in experimental psychology working with Michael Turvey at the University

of Connecticut. After graduating in 1995 she began working as assistant professor at The Pennsylvania State University where she has since established a productive research group. She has been Executive Editor of the *Journal of Motor Behavior* since 2005. Her interdisciplinary research program has several prongs: (a) the development of a unified framework for discrete and rhythmic movements with nonlinear dynamics as the theoretical framework, (b) a task-dynamic approach to a rhythmic movements with a special emphasis of the role of dynamical stability, (c) variability decomposition to understand learning and development, and (d) the detection of gait. The methods comprise an empirical component with behavioral experiments on human subjects, theoretical work that develops mathematical models for movement generation on the basis of coupled dynamical systems, and brain imaging studies (fMRI) to examine the cerebral activity. More recently, she has applied her experimental paradigms to neurological disorders such as Parkinson's disease and split-brain patients.

DANIEL M. CORCOS, Rapid Communications Editor of the *Journal of Motor Behavior*, obtained his doctorate in motor control from the University of Oregon in 1982 after obtaining his master's degree in psychology in 1980. Dr. Corcos was an assistant professor at the University of Illinois at Chicago from 1987–1993 and was promoted to the rank of associate professor with tenure in 1993 and to full professor in 1997. He served as Executive Editor of the *Journal of Motor Behavior* from 1997 to 2004. In addition to his work as the journal's Rapid Communications Editor, he is on the editorial board for the *Journal of Neuroengineering and Rehabilitation*. Dr. Corcos currently is involved in four lines of research. The first is related to the motor deficits associated with Parkinson's disease and how different neurosurgical interventions can facilitate the control of movement in Parkinson's disease. The second relates to the role of the basal ganglia in the control of a wide variety of movement tasks. The third relates to the central control of reflexes during voluntary movement. Finally, he is interested in the role of exercise in reducing the negative impact of progressive neurological disorders.

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