Multiple Time Scales and Multiform Dynamics in Learning to Juggle

Raoul Huys, Andreas Daffertshofer, and Peter J. Beek

To study the acquisition of perceptual-motor skills as an instance of dynamic pattern formation, we examined the evolution of postural sway and eye and head movements in relation to changes in performance, while 13 novices practiced 3-ball cascade juggling for 9 weeks. Ball trajectories, postural sway, and eye and head movements were recorded repeatedly. Performance improved exponentially, both in terms of the number of consecutive throws and the degree of frequency and phase locking between the ball trajectories. These aspects of performance evolved at different time scales, indicating the presence of a temporal hierarchy in learning. Postural sway, and eye and head movements were often 3:2 and sometimes 3:1 frequency locked to the ball trajectories. As a rule, the amplitudes of these oscillatory processes decreased exponentially at rates similar to that of the increase in the degree of phase locking between the balls. In contrast, the coordination between these oscillatory processes evolved exponentially at different time scales, apart from some erratic evolutions. Collectively, these findings indicate that skill acquisition in the perceptual-motor domain involves multiple time scales and multiform dynamics, both in terms of the development of the goal behavior itself and the evolution of the processes subserving this goal behavior.

Key Words: movement coordination, posture, eye movements, skill acquisition

Introduction

During the acquisition of a new perceptual-motor skill, performance typically improves gradually, although brief episodes of regression sometimes occur. The form of the improvement may be logistic, exponential, or hyperbolic, or abide a power law description (Mazur & Hastie, 1978; Newell, Liu, & Mayer-Kress, 2001), although it may be difficult to distinguish between these possibilities. Nevertheless, the exact form of learning curves may allow for empirical testing of theoretical

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predictions about learning as, for instance, has been the case for the chunking theory of learning, which predicts a power-law like behavioral change (Newell & Rosenbloom, 1981).

Until recently, considerations regarding learning curves were based on the qualitative form of the evolution of an outcome variable in the course of practice. K.M. Newell et al. (2001), however, suggested that the pattern of change observed at the level of the outcome variable is the product of the cooperation of distinct subsystems operating in parallel at multiple levels of analysis and at distinct time scales. According to this theoretical position, the regularities of change due to practice reside at the level of the changing dynamics of the subsystems rather than at the level of the outcome variable. In particular, K.M. Newell et al. (2001) showed that power-law like evolutions of outcome variables might come about by a concatenation of multiple exponentials with distinct time scales. The theoretical significance of this approach is that it formally maps the dynamics of multiple subsystems onto the outcome dynamics. As it stands, however, the approach has remained confined to the phenomenological level of the outcome variable(s) without addressing the differential functional dynamics of the subsystems involved in task performance. To date, it is largely unknown how those subsystems evolve and become embedded in a task-specific, effective organization. This process is well worth examining in detail so as to gain insight into the development of task-specific couplings between distinct subsystems, the manner in which these subsystems evolve at different time scales to support the macroscopic goal behavior, and thus the evolution of variables that are relevant to task performance.

Achieving a perceptual-motor goal often requires simultaneous as well as sequential performance of subtasks, such as picking up multi-modal information, maintaining postural stability, and generating muscle forces in interaction with the environment. Bingham (1988) and Bernstein (1996) explicitly recognized that efficient, goal-directed perceptual-motor behavior requires specialized subsystems to become assembled into a task-specific dynamical organization. This implies that, during learning, specialized resources become recruited and harnessed so as to achieve an overarching action goal. Bernstein further proposed that movements are constructed and controlled hierarchically at four functional levels, and argued that each control level has a certain degree of autonomy relative to the other levels and overall task performance. In a similar vein, Bingham emphasized that, due to the "inherent dynamics" of the subsystems, which are often nonlinear, the macroscopic behavior cannot be understood by means of simple summation of the behaviors of the subsystems, as appears to be assumed implicitly by K.M. Newell et al. (2001). Recently, these insights were confirmed for the evolution of postural sway, as novices learned to juggle the 3-ball cascade (Huys, Daffertshofer, & Beek, 2003), in that the stability of juggling performance and the dynamics of postural sway evolved in disparate fashion: Whereas the former improved gradually, the latter showed both gradual and abrupt changes in frequency locking. Is this the only evidence for the co-existence of distinct, relatively autonomous dynamical processes in learning? By no means.

Initial studies on (the acquisition of) juggling concentrated on spatial aspects of 3-ball cascade juggling (Van Santvoord & Beek, 1996) and on the manner

in which jugglers accommodate the primary temporal constraint on juggling as formalized by Shannon in his well-known juggling theorem, demanding frequency locking between hand and ball movements (cf. Beek & Lewbel, 1995; Horgan, 1990; Raibert, 1986). While these studies focused on a selection of discrete measures and were therefore, by definition, based on limited information, Post, Daffertshofer, and Beek (2000) examined covariance structures (in terms of principal component analysis, PCA) of the time-continuous juggling pattern (3 balls $\times$ 2 directions) in the frontal plane to identify its main components (rather than to select its main descriptors beforehand). Due to inherent symmetries, the juggling pattern could be represented by minimally two and maximally four frequency- and phase-locked modes. The number of components required for reconstructing the pattern varied with tempo, as the quality of performance decreased when speed of juggling increased from preferred to high. Building on these findings, Huys et al. (2003) investigated changes in the patterning of the balls during the acquisition of 3-ball cascade juggling. Besides an asymptotic improvement in the consistency and stability of performance, changes in time-continuous cross-links, as revealed by cross-spectral and relative phase analyses, suggested a reduction in the dimensionality of the control structure.

When studying changes in motor control in a complex perceptual-motor skill like juggling, changes in perception cannot be ignored. In various perceptual-motor tasks, such as pointing and grasping (Helsen, Elliott, Starkes, & Ricker, 2000), rhythmically throwing and catching a ball (Amazeen, Amazeen, & Beek, 2001), and various ball sports (Williams, Davids, Burwitz, & Williams, 1992), gaze is coupled to features of the environment that are relevant to performance. Generally, the degree of coupling between point-of-gaze and relevant environmental events is a function of practice. For instance, experts are known to pick-up information from earlier phases of an unfolding event, like an approaching ball, than novices (Amazeen et al., 2001; Helsen & Starkes, 1999; Williams et al., 1992; however, see Abernethy, 1990; Abernethy & Russell, 1987) and to direct their gaze earlier to the unfolding event than novices (Amazeen et al., 2001). Huys and Beek (2002) found that, in 3-ball cascade juggling, the point-of-gaze is often frequency locked to the ball movements and more so in intermediately skilled than in expert jugglers. The expert jugglers visually tracked the movements of the balls to a lesser extent and with smaller point-of-gaze excursions than the intermediate jugglers, probably because they relied more on peripheral vision, and kinesthetic and haptic information, than on foveal vision. This example suggests that, in the course of learning to juggle, changes in the relative importance of various information sources may occur, affecting the role of vision in the overall task organization.

Further examples of subsystems undergoing task-specific changes in their dynamics are found in studies on postural control, showing that sway becomes coupled to suprapostural activities, such as swinging the arms (Abe & Yamada, 2001) and visual tracking (Bardy, Marin, Stoffregen, & Bootsma, 1999; Bardy, Oullier, Bootsma, & Stoffregen, 2002). For instance, comparisons of the movements of novice and expert gymnasts, while visually tracking an oscillating target with a gradually increasing frequency of oscillation, showed that experts maintained the required in-phase hip-ankle coordination longer than novices (Marin, Bardy, & Bootsma, 1999). Similarly, the variability of body sway was found to be smaller

in experienced rifle shooters than in novices, while sway variability correlated only in the novices with task outcome (Era, Konttinen, Mehto, Saarela, & Lyytinen, 1996). Apparently, the expert shooters had fully integrated whole-body posture stabilization with shooting, whereas the novices had not. Although these works suggest that postural sway patterns differ as a function of expertise, studies of the actual evolution of the sway patterns during the learning of suprapostural tasks are few and far between (but see Huys et al., 2003).

Examining changes in motor control and embedding processes during the acquisition of perceptual-motor skills requires longitudinal studies of learning a task in which multiple subsystems cooperate to subserve performance. We therefore conducted a long-term experiment in which participants practiced to juggle a 3-ball cascade, while multiple signals were recorded repeatedly. Next to changes in juggling performance itself, we studied changes in the dynamics of various subsystems, namely postural sway and head and eye movements. The goal of the study was to examine the manner in which the changes in the dynamics of the subsystems relate to changes in task performance. To cast empirical light on the theoretical position of K.M. Newell et al. (2001), we were particularly interested in the (mathematical) form and the time scale of the changes occurring in the goal behavior itself and the processes subserving this goal behavior.

Evidently, searching for systematic changes in the dynamics of the subsystems implicated in 3-ball cascade juggling can be expected to be a fairly intricate affair. However, besides an increase in the number of consecutively juggled balls, extensive practice is likely to result in an asymptotic reduction of variability in the juggling patterns due to increases in the degree of frequency and phase locking between the ball trajectories (Beek & Van Santvoord, 1992; Huys et al., 2003) which, in principle, allows for detection of multiple time scales within the goal behavior itself. Furthermore, given the cyclic nature of juggling, similar changes in coordination may be expected to occur between the oscillatory features of postural sway, and head and eye movements on the one hand, and the ball trajectories on the other—opening up the possibility to examine how, and at what rate, these subsystems evolve in relation to the evolution of the goal behavior. Specifically, based on a previous study of postural sway in juggling (Huys et al., 2003), we expected to observe the occurrence of 3:2 and 3:1 frequency locking between postural sway and ball circulation, as well as switches between these locking modes. (See Huys et al., 2003, for explanations of these coordination modes in terms of their functionality and biomechanical background.) Similarly, based on a previous study of the coupling between point-of-gaze and ball movements during 3-ball cascade juggling (Huys & Beek, 2002), we expected to see the development of 3:1 frequency locking between eye and ball movements (indicating that a gaze shift is made to each tossed ball). Finally, again on the basis of previous results, we expected both types of coordination to evolve on a slower time scale than the improvement in juggling performance itself.

The vast literature on the control of posture and gaze/eye movements readily shows that a whole arsenal of analysis methods may be applied to address the present research question. To anticipate, in view of the intrinsic variability of the data, we will first attempt to extract reasonably "simple" learning behaviors. Amenable to such an analysis are saturation processes that can be quantified by

a single scalar value—namely, the characteristic learning time that represents the rate of change. However, to cope with instances that cannot be cast in this form, we will focus on correlation and covariance patterns, which will yield more general insights into the structural properties of the dynamical evolutions of interest. For the sake of readability, the discussion of the various analyses will directly follow the presentation of the results obtained before summarizing all pertinent findings in a concluding section.

Methods

Participants

Thirteen participants without any prior juggling experience (6 males, 7 females) participated in the experiment, after having given their informed consent. They varied in age between 17 and 31 years (mean = 21.2 years; *SD* = 3.8 years). They all had normal or corrected to normal vision.

Procedure

Before and after the practice schedule, all participants were tested with regard to their handedness and manual, visual, and kinesthetic abilities. The results of these tests and their correlation with juggling performance will be reported elsewhere.

Participants practiced in the laboratory for 1 hour per day on every workday for 9 consecutive weeks, up to a total of 41 hours. (During this period, there were 4 practice-free days.) Additional practice outside the laboratory was strictly forbidden. Each participant set out practicing the 3-ball standard cascade. During this initial stage of learning (stage I), 2-min recordings were made after each practice session, and the 10 attempts in which the participant had accomplished the highest number of consecutive throws were analyzed. Two hours of practice after a given participant was able to throw 30 or more consecutive balls during the recordings, he or she performed a number of additional experimental conditions that are irrelevant for the aims of the present study. During this second stage of learning (stage II, see Table 1), 2-min recordings were made after every other practice session. Fifteen practice sessions (hours) after a participant entered Stage II, he or she started (at the beginning of stage III) to practice juggling 4 balls for half an hour, dividing time equally over the in-phase (15 min) and anti-phase patterns (15 min), while continuing to practice the 3-ball cascade for the remaining half hour. The 4 slowest learners, however, remained on the 3-ball schedule. In this later stage of learning,

Table 1   The Moment (in Hours of Practice) After Which Each Participant Entered Stage II and Stage III of the Learning Regime

Participant	1	2	3	4	5	6	7	8	9	10	11	12	13
Stage II	31	10	4	7	5	31	15	6	11	12	7	15	12
Stage III	—	25	19	22	20	—	—	21	26	27	22	—	27

five attempts to juggle each of the 4-ball patterns were recorded after each practice session. In addition, 2-min recordings of the 3-ball cascade juggle were made once every week (that is, after every 5th practice session). In the later stages of learning, most participants were able to juggle continuously for 2 min. In these cases, a second 2-min recording was made. The present study focused on the results pertaining to the learning of the 3-ball cascade. Since only a few participants were able to juggle 4 balls sufficiently long to perform the here-applied analyses (see below), we will not present these results in the present paper. Note that we were unable to detect eventual influences of practicing the 4-ball juggle on the performance of the 3-ball juggle.
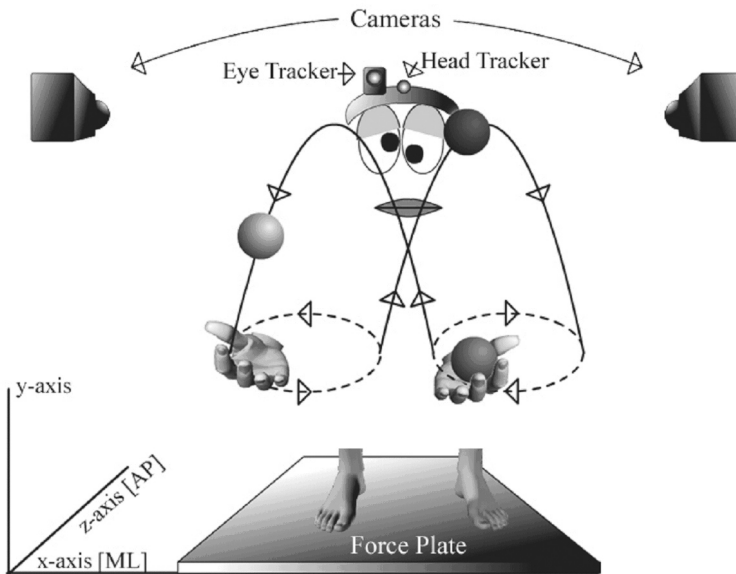

Figure 1 — The experimental set-up. (See text for details.)

Apparatus

All experimental trials were recorded with two video cameras at a sampling rate of 50 Hz, allowing for 3D reconstruction of the ball movements. (See Figure 1 for the experimental setup.) The cameras were suspended from the ceiling at an absolute height of about 2.90 m and a relative height to the middle of the scene of about 1.50 m. Distances to the scene in the horizontal plane were about 3.20 m and 2.00 m for the left and right cameras, respectively, and about 4.20 m in the sagittal plane. The video setup was calibrated every 1st day of a week by means of a 1.00-m $\times$ 0.75-m $\times$ 1.00-m calibration frame (height, width, and depth, respectively; equivalent to y-, x-, and z-axis, respectively). In addition, the participants were standing on a force platform (1.00 m $\times$ 1.00 m; sampling frequency 200 Hz) that measured the ground reaction forces by means of eight strain gauges. The force platform was

calibrated each day before the first experimental session. Eye movements (in the horizontal and vertical direction) were recorded by means of an ASL Model 501 head-mounted eye-tracking system (Applied Science Laboratories) at a sampling rate of 50 Hz. A head-mounted scene camera (50 Hz) was attached to the headband and recorded (part of) the field of view of the participant. (The footage of this camera was used for checking purposes.) A cursor was superimposed onto the recordings, indicating the participant's point-of-gaze. For each participant, the eye-tracking system was calibrated before each experimental session by means of a 9-point calibration frame. In addition, a head-tracker (Polhemus, 50 Hz) was attached to the headband to measure head translation and rotation (azimuth, elevation, and roll) in 3D. Simultaneously, both elbow angles were recorded by means of two goniometers (Biometrics, 200 Hz); these recordings were only used to determine the number of consecutive throws in trials longer than 30 s. For all recordings, time was encoded using a time-code generator. All recordings were synchronized (the video recordings indirectly by means of a flashing light). An example of the so-obtained time raw data is shown in Figure 2 for a single trial.
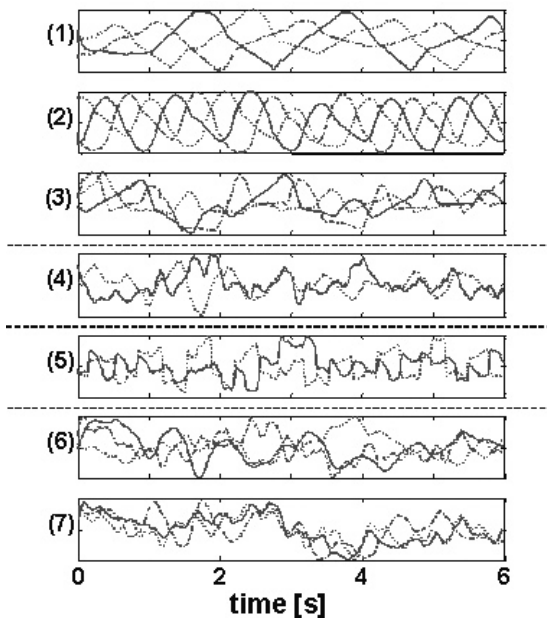

Figure 2 — An example of the raw data of a single trial. Panels (1), (2), and (3) show the 3 ball trajectories in the *x*-, *y*-, and *z*-direction, respectively; panel (4) shows the ML-sway (solid line) and AP-sway (dotted line); panel (5) the eye movements in the horizontal (solid line) and vertical direction (dotted line); panel (6) the head translations in the *x*-, *y*-, and *z*-direction (solid line, dash-dotted line, and dotted line, respectively); and panel (7) the head rotations azimuth, elevation, and roll (solid line, dash-dotted line, and dotted line, respectively). Note that, for purposes of visualization, each time series was divided by its absolute maximal value, rendering the units dimensionless.

Pre-processing

The video recordings were calibrated and the ball displacements were subsequently digitized in the x-, y-, and z-direction (WinAnalyze, Mikromak). Both center-of-pressure (CoP) components—that is, medio-lateral (ML) and anterior-posterior (AP) sway, corresponding to sway in the x- and z-direction, respectively—were computed from the 8 time series of the ground reaction forces. In order to obtain time series with an equal number of samples, the trajectories of the ball, eye, and head movements were interpolated by means of cubic splines, which resulted in an effective sampling rate of 200 Hz. To incorporate as many data points as possible while eliminating transients due to the start-up of the juggle, the first moment of zero velocity of the first ball after its first zenith was determined. This moment occurred immediately after the third ball had been thrown for the first time. Time series were excluded if they covered less than 6 consecutive individual ball cycles in the vertical direction. The length of the time series was adjusted to integer periods of the ball trajectories to improve the reliability of the spectral estimates (see below). Consequently, the time series of the balls started and ended with equal phasing. All other time series were aligned accordingly. We further eliminated the observed low-frequency components in the postural sway, and head and eye movements by means of a high-pass filter. However, since juggling frequency varied between participants and over days, all time series first had to be rescaled in time so that the vertical movements of the balls was always equal to 1.0 Hz (Table 2). As a consequence, the subsequent filter-settings were equal for all trials—that is, a high-pass filter cutoff frequency of 1.2 Hz. Note that prior to this preprocessing step, we had established that the juggling-related spectral content was dominant at 3/2 and 3 times the juggling frequency.

Table 2   The Mean and Standard Deviation of the Rescaling Factors Used for Rendering the Main Frequency of All Ball Trajectories in the Vertical Direction of the Entire Experiment 1 Hz for Each Participant

Participant	1	2	3	4	5	6	7	8	9	10	11	12	13
Mean	1.27	0.81	1.03	1.12	0.90	1.22	1.09	1.01	1.11	1.00	0.86	0.74	1.27
SD	0.14	0.02	0.15	0.08	0.16	0.11	0.06	0.10	0.05	0.04	0.05	0.06	0.07

Frequency-Locking Ratio and Strength

For all subsystems examined, the power spectral densities $P(\omega)$ were estimated by applying Welch's periodogram method (e.g., Stoica & Moses, 1997). To obtain the same frequency resolution for all trials irrespective of the individual lengths of the time series, we zero-padded all trials to the length of the longest trial before estimating the power spectral densities. (We used overlapping Hamming windows fixed at the length of the shortest trial.) The dominant frequency ω_0 was identified at the peak containing the most spectral power. Eventual cross-relations between different signals were quantified in terms of the ratio between their dominant

frequencies. In all analyses, the frequency of the vertical ball trajectory was used as a reference and served as numerator in the calculation of frequency ratios between component processes. Note that, by definition, 3-ball cascade juggling requires frequency locking between the ball trajectories in the horizontal and vertical direction and that higher numerical accuracy for the ball movements in the vertical direction is reached because, in this direction, the frequency of the ball movements is twice as high as in the horizontal direction. A $p{:}q$ frequency locking between projections of different subsystems was considered to be present if

$$\frac{(p \cdot \omega_{0,x} - \Delta\omega)}{(q \cdot \omega_{0,y} + \Delta\omega)} \leq \frac{\omega_{0,x}}{\omega_{0,y}} \leq \frac{(p \cdot \omega_{0,x} + \Delta\omega)}{(q \cdot \omega_{0,y} - \Delta\omega)}$$

where $\omega_{0,x}$ and $\omega_{0,y}$ denote the main frequencies of (arbitrary) time series $x(t)$ and $y(t)$, respectively, and $\Delta\omega$ is the frequency resolution of the corresponding spectral estimates. For each trial, the strength of frequency locking between the signals was quantified by means of

$$\psi_{x,y}(\rho) = 2N \frac{\int P_x(\omega) \cdot P_y(\rho \cdot \omega) d\omega}{\int \left[P_x^2(\omega) + P_y^2(\rho \cdot \omega) \right] d\omega}$$

where P_x and P_y represent the spectral densities of the (arbitrary) time series $x(t)$ and $y(t)$. Note that the integration only includes the frequency interval up to the smallest Nyquist frequency—that is, the actual sample frequency of the video recordings: 25 Hz; N is a normalization factor defined as $8N^2 = (\rho^2 + 1)/(\rho + 1)$. By fixing the ratio ρ at a specific value, one can always determine the strength of this specific frequency locking, regardless of whether this locking dominates the coordination between two time series. In the present experiment, the ratios 1:1, 3:2, and 3:1 were used depending on the subsystems examined (see Results). The more similar two spectra are after an appropriate rescaling ρ of the frequency axis, the larger their overlap and thus the higher the value of $\upsilon_{x,y}$ (ρ: see Daffertshofer, Peper, Frank, & Beek, 2000). In other words, the more two time series share a common "time base" (after appropriate rescaling), the stronger the frequency-locking strength $\upsilon_{x,y}$.

Relative Phasing

To address the time-dependent relative phasing between two projections $x(t)$ and $y(t)$, we used the Hilbert transform, as it provides an adequate estimate of the instantaneous phase and amplitude of an arbitrary signal (Gabor, 1946). Briefly, as complex extension of a real time series $s(t)$, the analytic signal $\zeta(t) = s(t) + I \cdot u(t)$ can be uniquely defined via

$$u(t) = \frac{1}{\pi} PV \int_{-\infty}^{\infty} \frac{s(\tau)}{t - \tau} d\tau$$

in which PV refers to the Cauchy principal value. As for every complex-valued quantity, one can introduce amplitude and phase in terms of $\zeta(t) = A(t) \cdot \exp[i$

$\cdot \Theta_H(t)$]—that is, $\Theta_H(t) = \arctan\{\mathbf{T}[\zeta(t)]/\mathbf{R}[\zeta(t)]\} = \arctan[u(t)/s(t)]$ defines the continuous Hilbert phase of the time series $s(t)$. The relative phase $\Delta\Theta_H(t)$ between two time series $x(t)$ and $y(t)$ is then defined as $\Delta\Theta_H(t) = \Theta_{H,y}(t) - _{H,x}(t)$ (see, e.g., Pikovsky, Rosenblum, Osipov, & Kurths, 1997, and references therein). As we were interested in cases of $p:q$ frequency locking, we generalized the latter definition in terms of $\Delta\Theta_H(t) = p\Theta_{H,y}(t) - q\Theta_{H,x}(t)$. For all trials in which frequency locking was observed, both the mean and the variance of the corresponding relative phases were computed using circular statistics (Mardia, 1971).

Cross-covariance

To evaluate the possibility of reducing the 9-dimensional time series representing the ball pattern (i.e., 3 balls × 3 directions), we subjected each individual trial to a PCA (cf. Post et al., 2000)—that is, we computed eigenvalues and eigenvectors of the covariance matrix based on the 9 time series of the ball trajectories. For each trial, the 9 time series were normalized with respect to the overall maximum variance before combining them into a state vector, $^l s(t) = [b_1^x(t), b_1^y(t), b_1^z(t), b_2^x(t), \ldots, b_3^z(t)]^T$. For each trial, the resulting eigenvalue spectrum was analyzed and, in addition, the time series were projected onto the individual eigenvectors (referred to as "projections"), after which these projections were subjected to spectral analysis as described above.

Extraction of Time Scales

To be able to extract and compare characteristic evolution times, we performed subsequent regressions on the basis of a single equation. As will become apparent in the Results section, we found learning curves that resembled linear, exponential, and (in a few cases) sigmoidal curves. Whereas the hyperbolic tangent function may capture all these forms, the number of parameters required (4) to do so renders the solution to the minimization of the regression equation non-unique (given the limited number of experimental data points; see the Procedure section and Table 1), and a reliable comparison of time scales may become problematic. Therefore, we concentrated on the exponential forms—that is, we used the function $A - Be^{-\lambda t}$ and determined its parameters via a simplex minimization of the corresponding least squares (Nelder & Mead, 1965), thus capturing all observed forms except the sigmoid. The rate of change is given by λ yielding characteristic times by means of $= 1/\lambda$. Recall that the characteristic time τ indexes the time to change a process's value by a factor of $1/e$ similar to a first-order linear response showing exponential decay/saturation (see Figure 3). In combination, λ and B may give rise to an exponential decay or saturation as well as to unbounded forms of change. The latter, however, are functionally irrelevant because frequency-locking strength and the variance of relative phase are bounded between 0 and 1. Indeed, in some instances, such unbounded, exponentially increasing curves were observed; however, we abstained from regressing them, as they necessarily indicate saturation (or transient behavior) on a time scale beyond that of the present experiment (except for the outcome measure of the number of consecutive throws). The limited number
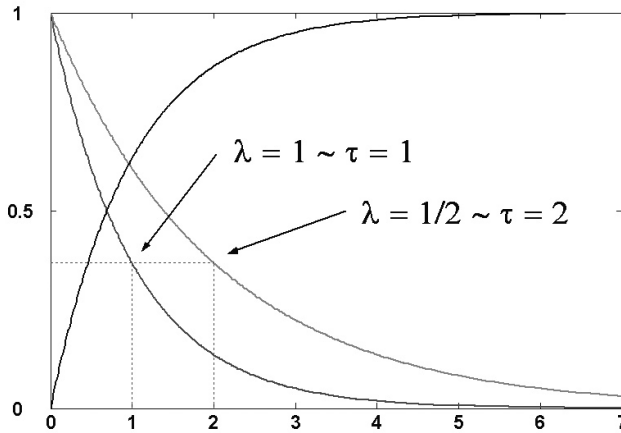
Figure 3 — Examples of exponentially saturating curves. The parameter settings for these curves were $A = 0$; $B = -1$; $\lambda = 0.5$ (decreasing solid curve); $A = 0$; $B = -1$; $\lambda = 1$ (decreasing dotted curve); $A = 1$; $B = 1$; $\lambda = 1$ (increasing dash-dotted curve).

of experimental data points renders the regression vulnerable to "noise" and outliers so that characteristic times can, in our opinion, only be viewed as distinct if they differ in orders of magnitude.

Results and Discussion

Number of Consecutive Throws

We first examined the changes in juggling performance in terms of a simple and intuitively appropriate outcome measure: the number of consecutively thrown balls. For 10 of the 13 participants, this number grew exponentially, albeit at a rate of change that varied widely across participants (see Figure 4). For the remaining 3 participants, the number of consecutively thrown balls saturated after an initial exponential increase.

Frequency Locking and Phase Variance

To further quantify the quality of juggling performance, we investigated the occurrence of common cyclic features in the ball trajectories. Frequency locking between the ball trajectories reflects the overall timing constraint immanent in the juggling task (i.e., Shannon's juggling theorem), while the locking strength indexes the degree to which the juggler satisfies this constraint. In other words, the locking strength reflects the degree to which the spectral content of the ball circulations is identical. Once the balls circulate at the same frequency (or period), a more fine-grained timing measure is provided by the variance of the relative phasing between the balls—that is, the degree to which a juggler succeeds in keeping
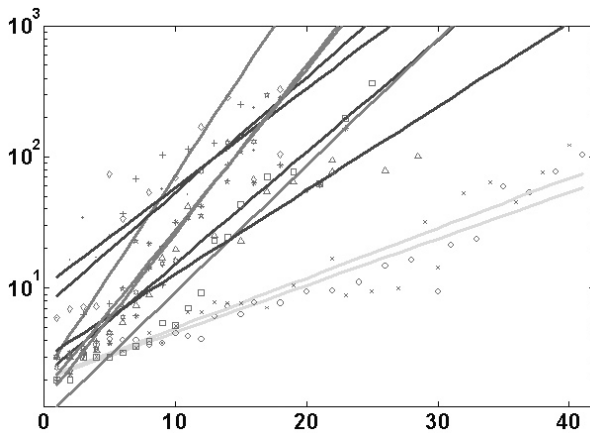
Figure 4 — The number of consecutively thrown balls (on a logarithmic scale) as a function of practice for the 10 participants showing exponential improvement. The slopes of the curves indicate the rate of change. Note that the solid, dashed, and dashed-dotted lines represent the learning curves of the fastest, intermediate, and slowest learners, respectively. (As indicated in the Methods section, most participants were able to juggle continuously for 2 min in the course of the experiment. As a consequence, the number of consecutive throws could not exceed the number reached at that moment. For visualization purposes, the fitted lines are extrapolated for these participants.)

the temporal distance between the balls constant. In all participants, juggling performance improved in that the strength of frequency locking between the ball trajectories increased and the variance of the relative phasing between the balls decreased. For most of the participants, the improvement of performance converged to fixed values within the practice period investigated. (Close to 1 for frequency locking and almost 0 for the phase variance.) In general, performance improved in terms of an exponential saturation when looking at the ball movements in the vertical direction. However, close inspection of the performance curves revealed that a rapid initial deterioration preceded this exponential change in 6 participants early in learning (see Figure 5). When the changes in performance appeared to be monotonic, some participants (5) improved so rapidly that exponential forms seemed to be absent, at least at first glance. To remove such initial trends, we applied two different regression procedures to the performance curves of interest (i.e., frequency-locking strength and variance of relative phase), one based on all the data except the initial non-monotonic changes (deterioration followed by improvement) and the other on all data except the very first sample. This allowed us to examine whether an early asymptote indeed implied that improvement was confined to the initial phase of practice. In all subsequent regression analyses, the second regression procedure was applied.

As regards the strength of frequency locking between the ball trajectories, 3 participants showed fairly erratic juggling patterns, whereas the remaining 10
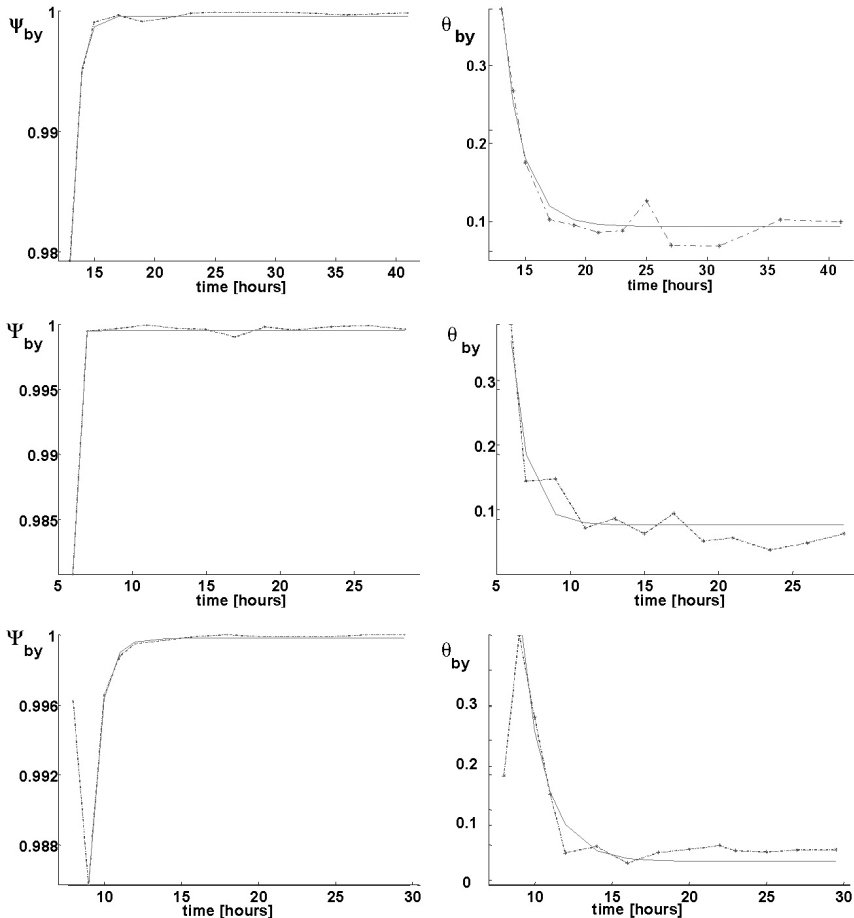
Figure 5 — Exponential fit of the evolution of the frequency-locking strength (υ; left panels—the solid and dotted lines represent the fit and the data, respectively) and the variance of the relative Hilbert phase (Δ; right panels—the solid and dotted lines represent the fit and the data, respectively) for 3 participants. Note the similar evolutions in the upper panels, the early asymptote for the frequency-locking strength, the slower evolution of Δ in the middle panels, and the initial deterioration in performance early in learning in the lower panel.

participants either showed a gradual, monotonic increase in locking strength or an already high, constant level of performance from the outset of learning onward. Two of these 10 participants showed a slow but persistent improvement in performance. Fitting exponential functions to these curves resulted in λ exponents of around 1.6 (h^{-1}), implying intrinsic characteristic learning times of about $\tau = .5$ h and slightly

less. The performance of the other 8 participants evolved rather slowly and resulted in estimated learning times of up to 100 days.

We subsequently examined the more fine-grained changes in timing by focusing on the variance of the relative phasing between the balls. In 5 of the identified group of 8 participants, as well as the 2 participants who improved in terms of frequency-locking strength, the variance of the relative phase between the balls decreased exponentially with estimated λ exponents between 0.2 and 1.0 (h^{-1}), corresponding to characteristic learning times of $\tau = 1$ and 5 h (5 + 2 = 7 participants). Thus, the majority of these participants showed an exponential decrease of the relative phase variance while being in a "steady-state" in terms of frequency-locking strength. The other 3 participants appeared to be close to their maximal performance level in terms of both frequency locking and relative phasing, as the variations in these measures were highly irregular. For a more detailed comparison of the time scales of the 5 + 2 = 7 participants (see below), we further re-estimated the growth rates of the outcome variable (number of consecutively thrown balls). This analysis showed that the outcome variable always changed slower than the variance of the relative phase. (In the following, we refer to the latter as the reference time scale, τ_θ.)

All these results indicate that the rate of performance improvement varied widely across participants, as was already observed subjectively during the experiment. However, the results also indicate that, in most instances, performance improved monotonically. In addition, the difference in time scales between the exponential increase in frequency-locking strength and the exponential decrease of phase variance suggests that the temporal fine-tuning of juggling (i.e., the variance of the relative phase) is usually adjusted markedly slower than the assembly of a "spatial clock" (cf. Beek, 1989, interpreted here as strength of frequency locking), which suggests that, in juggling, frequency and phase locking constitute two distinct parallel processes.

Having identified distinct time scales in the improvement of the goal behavior, we continued quantifying the learning curves in the recorded subsystems by focusing on equivalently continuous, exponential evolutions. As expected on the basis of earlier research (cf. Huys & Beek, 2002; Huys et al., 2003), we found the spectral content of body sway and eye movements to be distributed predominantly at 3:1 and 3:2 frequency-locking ratios with the ball trajectories. In addition, most of the recorded subsystems contained rather pronounced irregular, low-frequency, dynamical structures. Since these dynamical traces appeared to be random, and since our focus was on the relation between the subsystems and juggling performance—that is, on phenomena occurring at the time scales of the ball movements—we high-pass filtered the time series (using a cutoff frequency of 1.2 Hz) for the purpose of further analyses (see below).

In the following, we first report changes in frequency-locking strength without amplitude rescaling—that is, coordinative changes that are largely due to modifications of the amplitude of the oscillations. In addition, we report changes in "pure" coordination—that is, coordinative changes in which the amplitude effects were eliminated by rescaling the individual time series to unit variance. The latter results pertain solely to the temporal relations, or coordinative tendencies, between the oscillatory phenomena.

Amplitude-related Effects

Regarding the amplitude-dependent coordination (see Table 3), both sway components were usually 3:2 frequency locked to the ball trajectories; however, the strength of this locking mode strongly decreased in the course of practice. Except for 1 participant, the locking strength between AP-sway and the ball trajectories decreased exponentially, with characteristic times similar to those found for the aforementioned decreases in the variance of relative phase (i.e., $\tau \approx \tau$). Similarly, the reduction of the ML-sway was exponential, with comparable characteristic times, although in several participants, it appeared to be linear rather than exponential.

Similar to the results for postural sway, we found 3:2 frequency-locking ratios between eye movements and ball trajectories in both directions. In the horizontal direction, instances of 3:1 locking were observed as well (see also Huys & Beek, 2002). The evolution of both locking modes was rather variable and, in general, both increases and decreases were present. As a result, the observed changes were rarely exponential but, if so, the magnitude of the characteristic time was often in the order of magnitude of τ, although less clearly so in the horizontal direction. These results differ from those obtained for body sway, and one may speculate that such differences were due to the distinct physical properties of both subsystems, such as differences in inertia. Recall, however, that we eliminated low-frequency components in the individual time series so that such physical effects were suppressed. Thus, the characteristic times related to the learning dynamics rather than to the response times of physical devices. When the passive biomechanical properties would be of overarching importance, one would expect the head movements to evolve similarly as the sway components. In fact, however, the 3:2 frequency-locked oscillations of the head movements in the *x*-direction decreased less consistently (in 4 participants)

Table 3   Incidences of the Characteristic Times τ of the Evolution of the Amplitude-Dependent 3:2 Frequency Locking Strength of the Subsystems Relative to τ_θ

τ	ψ	θ	$ML^{3:2}$	$AP^{3:2}$	$Ex^{3:2}$	$Ey^{3:2}$	$Hx^{3:2}$	$Hy^{3:2}$	$Hz^{3:2}$	$Az^{3:2}$	$El^{3:2}$	$Ro^{3:2}$	
10			1	(1)				(2)	1		1	1 (1)	4 (4)
1	2	7	3	5	2 (1)	2	2	1 (2)	2	1	3	3 (2)	24 (5)
10^{-1}				1	1 (1)		2	3 (1)					7 (2)
100^{-1}								1	1	2	1	3 (1)	8 (1)
Steady	5				2	3	1		1	2			9
Others			4		2 (4)	2	2	2 (2)	2	2	2	(3)	18 (9)

Note. Parenthesis indicates the number of observations for subsystems in which considerable 3:1 locking was observed.

than the 3:2 frequency-locked sway oscillations while, in the other directions, the 3:2 locked oscillations decreased in all participants. In most cases, the observed reduction was exponential, with characteristic learning times ranging from $\tau/100$ to about τ. Similar patterns were observed regarding the head rotations, but the amplitudes of the coordinated oscillations always decreased, and characteristic times of about $\tau/100$ were more common.

Changes in Coordination

The changes in the subsystems' frequency-locking strength to the ball movements reported thus far were detected using analyses without amplitude rescaling. That is, "pure" coordinative effects may have been obscured by amplitude adjustments. By rescaling the amplitude of each individual time series such that their variances equaled 1, we eliminated all amplitude effects and focused solely on coordinative tendencies.

As was the case for the amplitude-dependent effects, 3:2 frequency locking between the subsystems of interest and the ball trajectories was found to prevail over 3:1 frequency locking, especially for AP-sway, the eye movements in the vertical direction, and the head movements in the horizontal direction (98%, 98%, and 95% of all trials, respectively). In contrast, pronounced 3:1 frequency locking was observed in the eye movements in the horizontal direction, the head movements in the vertical direction, and rolling movements of the head (32%, 54%, and 32% of all trials, respectively).

Subsequently, we examined whether the strength of the most dominant locking changed with practice (see Table 4). In contrast to the non-rescaled amplitudes, the AP-sway, the eye movements in the vertical direction, and the head movements in the horizontal direction, all exhibited rather steady 3:2 frequency locks with the ball trajectories so that extracting characteristic times led to estimations in the order of magnitude of around $\tau \approx \tau/10^{-5}$—that is, years (cf. above). Although an experimental verification (or falsification) of such long time scales is cumbersome, it seems fair to say that, in view of the large differences between the characteristic

Table 4   Incidences of the Characteristic Times τ of the Evolution of the 3:2 Frequency Locking Strength of the Subsystems Relative to τ_θ (Pure Coordination)

τ	ψ	θ	$AP^{3:2}$	$Ex^{3:2}$	$Ey^{3:2}$	$Hx^{3:2}$	$Hy^{3:2}$	
10			1	1 (2)	1	1	(1)	4 (3)
1	2	7		(3)			(1)	0 (4)
10^{-1}				(1)			(1)	0 (2)
100^{-1}							1(1)	.. (..)
Steady	5		5	1	5	5	1(3)	17 (3)
Others			1	5 (1)	1	1	5	13 (1)

Note. Parenthesis indicates the number of observations for subsystems in which considerable 3:1 locking was observed.

time scale of the goal behavior (i.e., the variance of the relative phase) and the time scales of changes in the AP-sway, the vertical eye movements and the horizontal head movements, these subsystems had little impact on the fine-grained timing between the balls (and vice versa).

For the 3:1 frequency-locking strength, especially for the eye movements in the horizontal direction, a different pattern was found: Rather than a steady coordination, the strength of this locking mode increased exponentially in all participants (except for the 2 participants in whom the amplitude decreased as well). One may speculate that the differences between the horizontal and the vertical direction might have been caused by differences in the predictability of the ball movement, since the constant acceleration due to gravity is experienced daily, whereas the (almost) constant velocity along the horizontal direction is throw-dependent. Notwithstanding the structural evolution of the 3:1 locking strength of the eye movements in the horizontal direction, switches between the 3:1 and 3:2 locking modes often occurred. Head movements turned out to be even more irregular; all participants showed frequent switching between 3:1 and 3:2 frequency locking. Since none of these switches revealed a consistent pattern, they will not be discussed further.

In sum, the amplitude of the 3:2 frequency-locked oscillations of the sway components (AP most pronounced) as well as of the head movements decreased in a consistent manner. Such clear and consistent patterns of coordination were found less often for the eye movements. Roughly speaking, body sway, head movements, and (to a lesser extent) eye movements often showed characteristic learning times similar to that of the temporal fine-tuning of the juggling itself. In contrast to these amplitude effects, the strength of the 3:2 frequency locks was steady for the AP-sway, the eye movements in the vertical direction, and the head movements in the horizontal direction. Only the 3:1 frequency locking of the eye movements in the horizontal direction was found to consistently increase exponentially, albeit at rather variable time scales.

Correlation Analyses

Thus far, we focused on the temporal aspects of structural changes by extracting characteristic times over which functionally distinct subsystems evolve. In doing so, we had to restrict the analyses to cases in which participants followed exponential learning curves. In addition, we examined possible links between performance and the subsystems by correlating the performance curves (i.e., the variance of the relative phase as a function of practice) and the frequency-locking strength at the 3:2 and 3:1 locking ratio as a function of practice for each participant. Since all participants could be included in this analysis, we also compared these correlations between the group that continued learning ("fast learners"; 5 + 2 = 7 participants) and the group whose performance improved only initially ("slow learners"; 3 + 3 = 6 participants). In line with the previous analyses, we studied every subsystem with and without amplitude rescaling. For the amplitude-dependent coordination at the 3:2 locking mode, we found positive averaged correlations between the variance of the relative phase and the locking strength of ML- and AP-sway, the

head movements in the y-direction, azimuth, elevation, and roll ($r \approx 0.46, 0.51$, 0.39, 0.33, 0.42 and 0.39, respectively; means were calculated over all correlations, significant or not, with the proviso that, in minimally 10 of the 13 participants, the sign of the correlation was the same). Regarding the 3:1 locking mode, a positive averaged correlation was found for the head movements in the y-direction ($r \approx 0.64$). These positive correlations indicated that strong amplitude-dependent frequency locking and "poor" performance seemed to go hand-in-hand, regardless of learning rate (i.e., no significant group differences were found for any of these correlations). In contrast, when considering pure coordination, results changed dramatically. For the 3:2 locking ratio, all correlations basically vanished. For the 3:1 frequency-locking ratio, only the eye movements in the horizontal direction were correlated on average to performance ($r \approx -0.36$). Furthermore, this averaged correlation was substantial for the fast learners ($r \approx -0.52$) but was absent for the slow learners. These results suggested that, indeed, large amplitudes of the oscillations in the subsystems impoverished performance. Although correlations should not be interpreted erroneously in causal terms, it seems likely that "poor," unstable performance sometimes resulted in uncorrelated body sway. On the other hand, for the 3:1 locking of the horizontal eye movements, amplitude appeared to be less important; in contrast, coordinated looking behavior may "aid" juggling performance, at least, in the present group of novices.

The correlation analysis also allows for a more quantitative discussion with respect to the switches that occurred between the 3:2 and 3:1 frequency-locking ratios observed in the eye movements in the x-direction, the head movements in the y- and z-directions, and the head rotations. In order to quantify such relations, we calculated the ratio of the frequency-locking strengths $\upsilon_x^{3:1}$ and $\upsilon_x^{3:2}$, and subsequently examined the cross-correlation between the so obtained time series. For one participant (a "fast" learner), we found significant correlations in the locking dynamics between AP-sway and the vertical head movements ($r = 0.68, p < .05$), azimuth ($r = -0.66, p < .05$), and roll ($r = 0.77, p < .05$), and between azimuth and roll ($r = -0.72, p < .05$). Apart from this participant, in whom many evolving subsystems were correlated, incidental pair-wise correlations were found in all participants. However, in view of the lack of consistency across participants, we did not further pursue this aspect.

In sum, the patterns of correlations showed that, whereas large amplitudes of the 3:2 coordinated oscillations of both body sway components and head movements occurred in conjunction with unstable juggling performance (in terms of a large variance of the relative phasing between the balls), regarding pure coordination, adopting the 3:1 frequency locking of the horizontal eye movements seemed to aid juggling performance, and its presence distinguished the fast from the slow learners.

Recall that next to the aforementioned abrupt changes in locking strength, we reported initial discontinuities in performance in 6 participants. Indeed, the quality of the performed juggle appeared to depend on the strength of coordination between (some of) the subsystems and the ball trajectories; nevertheless, it could not be firmly concluded that specific subsystem-related constraints were responsible for the observed discontinuities in performance. Therefore, we finally examined

eventual changes in the spatio-temporal structure of the ball movements in the course of learning by looking at changes in their covariance patterns in the course of practice.

Covariance Analyses

PCA applied to the ball trajectories revealed that the eigenvalues converged in the course of learning (see Figure 6 for an example). On average, the first two modes initially covered 70% of the variance of the entire 9-dimensional space and 78% at the last day of learning. By implication, the variance covered by the remaining modes decreased. Besides overall changes in the distribution of the variance, the (absolute value of the) eigenvectors corresponding to the 9 modes indicated how the contribution to the most prominent modes changed as a function of practice: In general, the contribution of the ball movements in the *y*-direction to the first two modes gradually increased, whereas those along the *x*- or *z*-direction decreased. (The relative extent of vanishing contribution of *x*- vis-à-vis *z*-directions was rather variable across participants; see Figure 7 for an example.) In other words, throughout learning, the spatial variability of the entire 9-dimesional juggling pattern changed, such that the dominance of the ball movements in the *y*-direction became more prominent, and the juggling pattern changed from a "flat" rotated figure-8 pattern spread along all three Cartesian coordinates to a "steeper" figure-8 pattern confined primarily to the frontal plane. In 1 participant, this spatial re-organization was so pronounced that it resulted in an abrupt switch in the dominant direction from horizontal to vertical (see Figure 8). Interestingly, this transition coincided with the initial deterioration in performance. Considering, however, that such an abrupt switch between dominant principal modes was only detected in 1 participant, it cannot explain the initial deterioration seen in the other 5 participants.
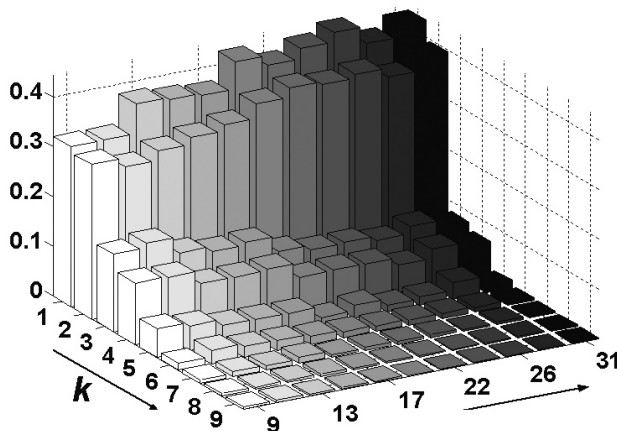

Figure 6 — Eigenvalue spectrum of the ball trajectories for 1 subject as a function of learning. Note that the amount of variance accounted for by the first two modes λ_k gradually increases.
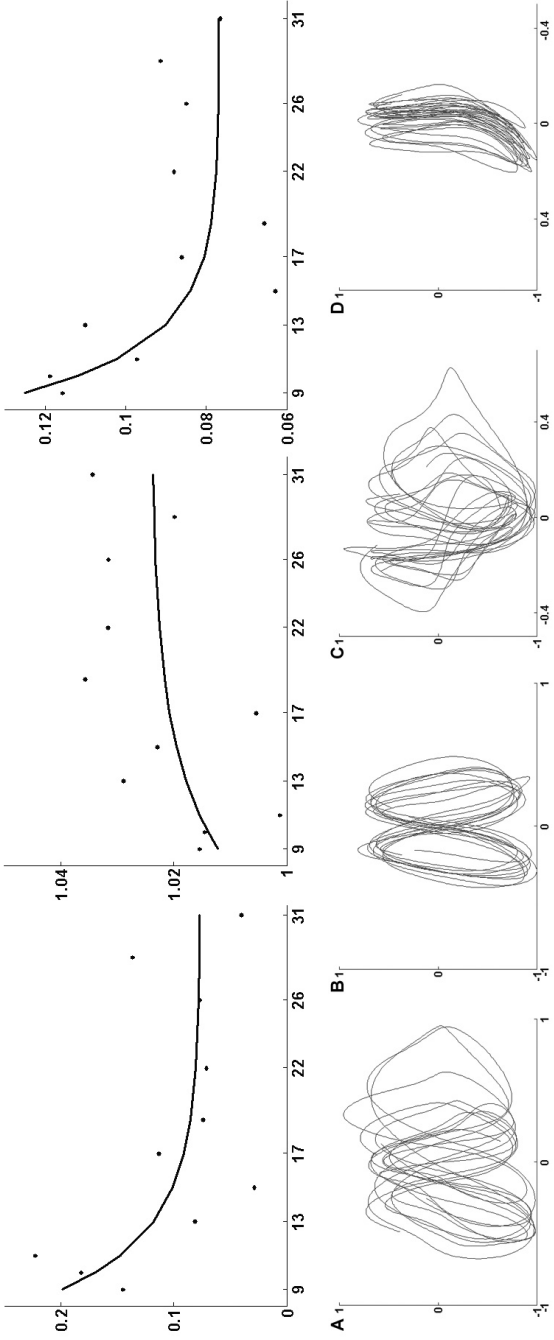
Figure 7 — (a) Evolution of the eigenvectors pertaining to the first two modes for the balls in the x-, y-, and z-direction (same participant as in Figure 6) as a function of learning (upper row, panels 1, 2, and 3, respectively). For each direction and each day, the absolute values of the eigenvectors of the 3 balls were averaged and subsequently summed for the first two modes. Note the decreasing contribution of the x- and z-directions and the increasing contribution of the y-direction. (b) The spatial reorganization can be further appreciated from the bottom row, displaying the raw data corresponding to first (A/C panels) and last (B/D panels) data points of the upper row (i.e., days). The ball trajectories in the xy-plane and yz-plane are plotted in Panels A/B and C/D, respectively.
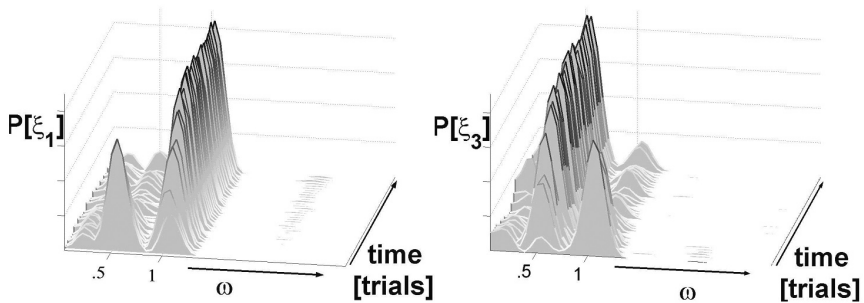
Figure 8 — Spectral density estimates of the projections of the first (left panel) and third (right panel) mode, ξ, of the 9-dimensional ball pattern as a function of practice. ω denotes the frequency axis, which was rescaled to the dominant frequency of the ball movements in the *y*-direction. Note that initially, the projections of the first mode correspond to the dominant frequency of the ball movements in the *x*-direction and the transition to the frequency corresponding to the dominant frequency of the ball movements in the *y*-direction.

To approach this topic in an unbiased manner, we computed the covariance function between learning curves using the improvement of performance in terms of frequency-locking strength as reference. Either the lag-zero or the lag-one covariance with the evolution of the variance of relative phase turned out to be maximal (in absolute values), indicating that the non-monotonic change in frequency-locking strength either coincided with or was preceded by an increase in the variability of relative phase. Interestingly, similar extrema in the covariance function were detected for the change in postural AP-sway amplitudes showing that the (non-monotonic) change of this component also coincided or preceded the change in frequency locking. Comparable lag-covariances were not found in the other subsystems, indicating a primary relation between AP-sway/relative phasing and local deterioration of the quality of overall timing as reflected in the strength of frequency locking.

General Discussion and Conclusions

In the present study, we examined how juggling performance, postural control, and head and eye movements evolved as novices learned to juggle the 3-ball cascade. As has commonly been found in studies of motor learning (A. Newell & Rosenbloom, 1981; K.M. Newell et al., 2001; K.M. Newell & van Emmerik, 1989; Vereijken, Whiting, & Beek, 1992), juggling performance improved monotonically. Juggling performance was operationalized in terms of the number of consecutive throws and in terms of the degree of frequency and phase locking between the balls being circulated. The number of consecutive throws increased exponentially. With practice, the strength of frequency locking between the ball trajectories increased and the variance of the relative phasing between the balls decreased. The increase in frequency-locking strength occurred quicker than the decrease in the variance

of relative phasing. This suggests that learning to juggle involves learning to satisfy (at least) two timing constraints: namely, the global temporal constraint of matching the frequencies of the balls, resulting in a "spatial clock" with a fixed (ball-independent) time base (cf. Beek, 1989) and the more local requirement to achieve a constant relative phasing (i.e., equal temporal distances) between the balls. Participants either improved both aspects in parallel at different rates or virtually started out with a fixed degree of frequency locking and only reduced the variance of the relative phasing. Thus, learning to juggle involves two kinds of constraint satisfaction: a quick adaptation to the global temporal constraints (frequency locking) and a markedly slower adjustment to the more local requirement to fixate the time intervals between the balls (relative phasing).

In general, frequency locking is a prerequisite for phase locking. An efficient strategy for learning to juggle is therefore to first achieve frequency locking before reducing the variance of relative phase, as was indeed the case in most participants. Deviations from this strategy seemed to be detrimental to the overall timing of the juggling performance, resulting in lower frequency-locking strength. Given our results of lag-zero versus lag-one covariance patterns in participants showing non-monotonic changes in frequency-locking strength, it seems likely that those participants tried to quickly adjust the relative phasing between the balls, which worsened the overall juggling performance. In other words, the two adjustments normally evolve on different time scales that, in spite of their simultaneous operation, appear to be characterized by a certain hierarchical order: first frequency locking and then reduction of relative phase variance. Disrespecting this hierarchy results in a deterioration in the quality of performance. Recall that these time-continuous measures reflect the stability of juggling performance and also contain information about the dynamics of the end-effectors. That is, they defy the traditional distinction between outcome and its generation. Interestingly, the identified hierarchical order above seems to extend to the primary outcome variable (i.e., the number of consecutive throws, which always increased at a slower rate than the variance of the relative phase decreased). In sum, the present results suggest a temporal hierarchy in the evolution of the goal behavior, implying that already in the production of the goal behavior itself, multiple time scales are operative, as we expected on theoretical grounds.

Further evidence for Newell et al.'s (2001) position was that multiple time scales and multiform dynamics are present in the learning of a complex perceptual-motor skill was found in the evolution of the relations between the subsystems (i.e., postural sway, and eye and head movements) and the goal behavior. Interestingly, the results for the subsystems differed significantly when distinguishing between amplitude-related and "pure" coordination effects. When preserving the amplitude effects, we found distinct coordination patterns relative to the ball movements for both body sway and eye and head movements: As expected, 3:2 and 3:1 frequency locking prevailed (cf. Huys & Beek, 2002; Huys et al., 2003). In the subsystems with high inertia, the amplitudes of the oscillations decreased on average in a manner similar to the decrease in the variance of relative phase. While the sway amplitudes were reduced at a time scale similar to that of the reduction in the variability of relative phase, the amplitudes of the head movements often decreased much more

quickly. In contrast, when focusing on "pure" coordination (i.e., by eliminating amplitude effects), the positive correlations for the 3:2 frequency-locked sway and head movements vanished and did not show any structural changes in the course of learning. However, the 3:1 frequency-locked horizontal eye movements became (negatively) correlated, but only in the fast learners, implying an increased coupling between ball movements and looking behavior in this group. In addition, the latter coordination often changed at time scales similar to that of the increase in the degree of phase locking between the ball trajectories. The absence of correlations and structural changes in the course of learning for sway and head movements suggests that the pure frequency locking of these subsystems is less important for the quality of juggling; for postural sway, this result confirms our previous findings (Huys et al., 2003).

These results also allow for an alternative interpretation. Although the coordination between the subsystems and the ball trajectories evolved extremely slowly, if at all, the strength of these frequency locks was rather high. If these coordination modes were of limited importance to juggling, then the spectral correlations would be less pronounced, and the observed patterns of change less structured. Thus, one may speculate that the biomechanical and informational constraints on juggling are such that the 3:2 locking is almost inevitable or that the coordination is so important that the necessary adjustments already occurred before performance could be quantified. Although the importance of the degree of coordination may be disputable, controlling the amplitude of the coordinated oscillations clearly mattered. Both postural sway and head movements reflect, or at least contain, the dynamics of the center of mass of the entire body. At first guess, one would therefore expect them to evolve at identical time scales. Because head movement amplitude is reduced so rapidly, however, it seems to be important to "fixate" the head position relative to the juggling patterns, probably in order to stabilize the perceptual input. With this rapid reduction of head movements, a similarly quick adjustment of the eyes' movement amplitudes becomes less important (and indeed was not consistently found). Instead, "fixating" the head may precede the development of pure coordinative coupling of the horizontal eye movements to the balls, as it optimizes the boundary conditions for this functional coordination to develop. Perhaps head movements can be seen as the coarse-grained component and eye-movements as the fine-grained component of the visual system.

Returning to the issue of multiple time scales in most general terms, Newell et al. (2001) suggested that there are potentially many indices of change in motor behavior and many time scales over which the change in behavior occurs. Our present results confirm this suggestion: We found evidence for different processes operating at time scales differing in orders of magnitude (>100, and possibly more). Besides exponential changes (see also Liu, Mayer-Kress, & Newell, 2003), we found sigmoid, erratic, and almost linear progressions. Intriguing questions for future research pertain to the principles underlying these functional forms, such as: What are the dynamical underpinnings of these differences in time scales? Do they merely reflect the dynamics of the particular subsystem measures in which they are found, or are they also the product of interactions with other processes?

As regards the functional form of learning curves or, at least, dynamical changes in (specific) subsystems, some final remarks are called for. Although power laws are still rather popular, individual learning curves are often described more accurately using logistic, exponential, or hyperbolic function (cf. Brown & Heathcote, 2003; Heathcote, Brown, & Mewhort, 2000). In the present study, we were interested in comparing the time scales of the evolution of various dependent variables, pertaining either to the goal behavior or to specific subsystems. To allow for such a comparison, we had to use a single function to extract the time scales of the evolutions of interest. Considering that most of these evolutions saturated, we chose to fit an exponential function to the data. This choice should neither be seen as unique nor as one guaranteeing an optimal data fit. Longitudinal learning studies of tasks involving a plethora of subsystems will inevitably suffer from low temporal resolution and limited accessibility of relevant subsystems. Hence, the choice of a specific functional form will always remain arbitrary, at least to a degree. Indeed, when one restricts the analysis to a single monotonic functional form (e.g., logistic, exponential, or hyperbolic), every non-monotonic change implies that the recorded signal either stems from a combination of underlying subsystems or that changes in performance are caused by non-trivial interactions. In any case, it is impossible to describe such dynamical changes with the aforementioned functional forms. Whereas learning rates may be useful in detecting possible temporal hierarchies in the assembly of subsystems into a dynamical organization, they neglect magnitudes of change, which in all likelihood, are important from a functional point of view.

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