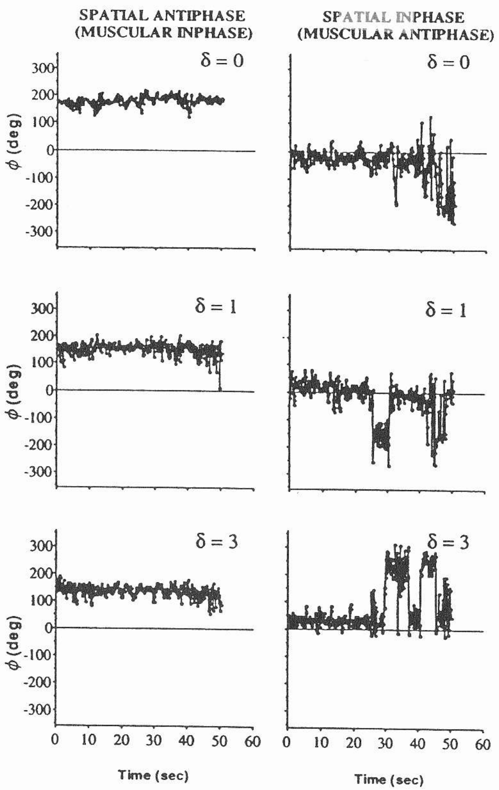

Figure 3. Examples of destabilization under the different δ conditions from one participant. The relative phases on the vertical axis are in spatial coordinates. As in Figure 2, movement frequency is increasing over the 50 s trial. The muscular antiphase mode shows more destabilization at higher movement frequencies than the muscular inphase mode, with the form of the coordination breakdown dependent on δ.

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Scale-Invariant Memory During Functional Stabilization

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Current models of coordination typically exhibit dynamics that are restricted to *stable* states such as limit cycles and point attractors (e.g. Treffner & Turvey, 1996). Mode-locking, if present, means fixed phase- and frequency-locking. Recent experiments indicate that perception-action might also be construed as an open, self-organizing complex system that exhibits great flexibility by operating near by critical instabilities (Kelso, 1995). This provides the system with the possibility of generating appropriate control strategies across multiple spatial and/or temporal scales (Treffner & Kelso, 1995). In sum, complex systems exhibit scale-invariance by exploiting *unstable* dynamics. Complementary to the analysis of the local dynamics of nonlinear transition phenomena, one can inquire whether a global analysis focusing on the statistical properties of the ensemble of trials also yields signatures characteristic of a dynamical self-organized system. In order to investigate the harnessing of instability, we investigated the dynamics of balancing an inherently unstable, inverted pendulum in a functionally stable manner.

Method

Four right-handed graduate students attempted to balance an aluminum rod that was constrained to slide laterally along a 180 cm track positioned at waist level. The pivot housing at the base of the rod could be easily moved from side to side by the subject's right hand.

Six different lengths were tested: 30, 45, 60, 75, 90, and 105 cm, with corresponding eigenperiods of 1.10, 1.35, 1.56, 1.74, 1.90, and 2.06 s.

Beginning with the longest and ending with the shortest rod, each subject attempted to balance continuously for 300 s. Using an Optotrak, displacement data of the bottom of the rod (the hand) and the top, sampled at 100 Hz, provided a raw time series of 30,000 points from which the angle from vertical was also computed.

Since the trajectory of a balanced rod appears similar to a random walk, the Hurst exponent, H, was calculated. For purely random (Brownian) motion, $H = 0.5$, indicating that no correlation exists between a point and all other points. In contrast, with $H > 0.5$, the direction of past changes is preserved (global positive correlation called "persistence"), i.e., decreases (increases) in the past will be followed by decreases (increases) in the future. With $H < 0.5$, the direction of past changes is reversed (global negative correlation called "antipersistence"), i.e., decreases (increases) in the past will tend to be followed by increases (decreases) in the future (Bassingthwaighte et al, 1994). Processes with $H \neq .5$ are considered as random fractals due to such scale-invariance. Following Hurst's empirical relation ($R/S = DT^H$), scaling is revealed if a linear region exists in the log-log plot of R/S versus DT, where R is the range of the *raw* time series for a given window size (with DT a power of 2), S is the standard deviation of the *increments*, and a mean R/S is calculated for each window size.

Results

Figure 1 displays plots of the grand mean (over all subjects and lengths) of R/S for hand displacement, the purported action variable. Two linear scaling regions exist: a short-term, persistence region ($H = .95$), and a long-term, antipersistence region ($H = .29$). In addition, a crossover region exists between them at 2.6 s. The long-term scaling implies a kind of "memory" in the global perception-action dynamics for a duration of 80 seconds into the past. A similar result was revealed for the purported perception variable, angle of rod: short-term persistence ($H = .94$), and long-term antipersistence ($H = .15$). However, the crossover at 1.3 s occurred earlier for the angle than for the hand. This may be due to the much greater constraint placed on how far the rod can move from vertical in comparison to the much less constrained movement of the hand.

The crossover between persistence and antipersistence was also revealed by plotting the local slopes (local estimates of H) against DT. Figure 2 indicates that the transition between persistence and

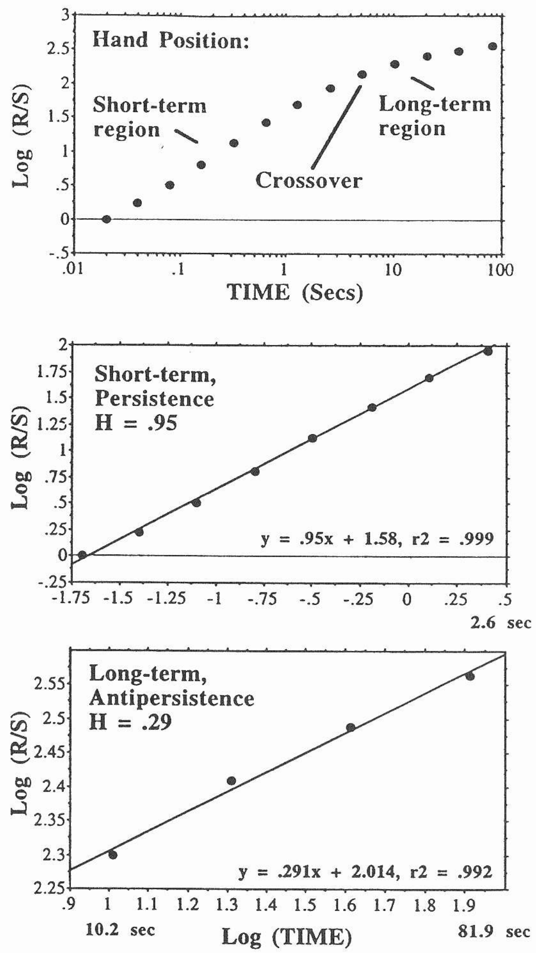

Figure 1. Top: Overall Hurst plot for the action variable (hand displacement) where R/S was collapsed across all subjects and all rod lengths. Two linear scaling regions are apparent. Middle: The short-term region from the top graph indicating persistence up to 2.6 s. Bottom: The long-term region from the top graph indicating an antipersistence memory of 80 s.

antipersistence occurred almost 6 s earlier for the rod angle than for the hand. Importantly, the rod's natural frequency (constrained by rod length) determined the crossover point for the angle variable in a consistent manner. Thus, shorter (difficult) rods led to earlier transitions to antipersistence than did longer (easier) rods.

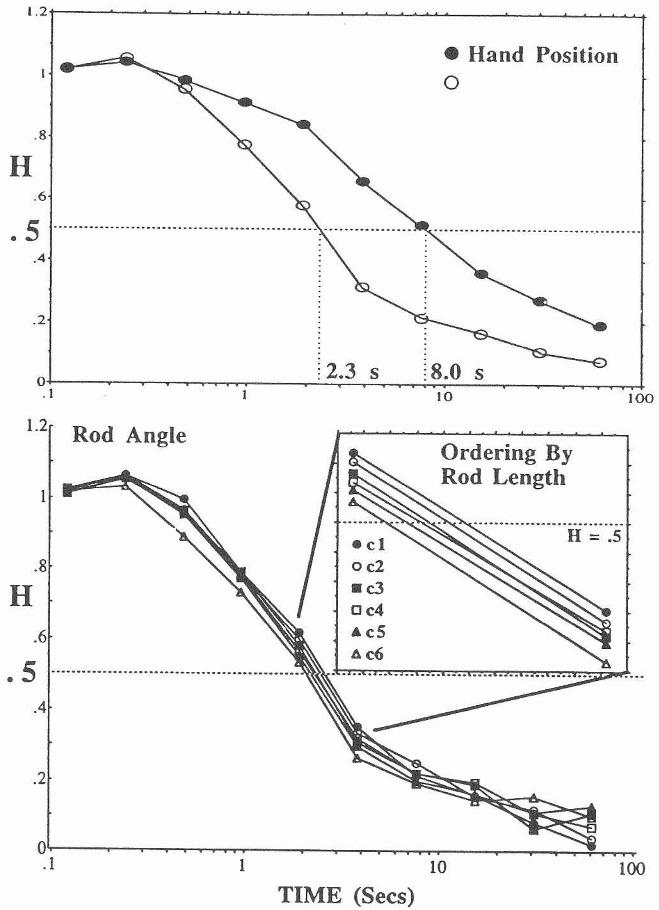

Figure 2. Top: Transition diagram for the collapsed data, showing that the switch in H from persistence (H > .5) to antipersistence (H < .5) occurs earlier for the perceptual variable (angle) than for the action variable (hand displacement). Bottom: Transition diagram for the angle, showing the influence of rod length on the angle's crossover point (inset). C1-C6 = long through short rod length conditions.

Since the extent of the estimated long-term "memory" is limited by the largest window of DT, a single, uninterrupted 30 minute trial was produced by an expert subject. Analysis revealed that for the hand, linear persistence (H = .87) switched at 3.2 s to antipersistence (H = .25), and this held for 3.4 mins into the past. For the angle, persistence (H = .86) switched at 1.6 s to antipersistence (H = .27), and also held for 3.4 mins. Interestingly, from 3.4 mins to 13.6 mins for the angle, H = .48, corresponding to purely random behavior. Thus, beyond 3.4 mins, all correlation was lost implying an upper bound on the system's memory.

We have shown that the dynamics of active stabilization may be characterized as a stochastic process. More than mere description, such characterization impels alternative notions of formative organizational mechanisms. Further, we have shown that the extrinsic mechanics (rod length) influences the stochastic dynamics in a principled manner. Finally, the long-term correlation inherent in the perception-action dynamics suggests that phenomena such as "memory" might be recast in terms of generic mechanisms of self-organization (Treffner & Kelso, 1996).

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