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Dimensionality and the Dynamics of Human Unstable Equilibrium

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ABSTRACT. Maintaining an unstable equilibrium requires that multiple joints be coordinated so that the center of mass is kept above the base of support. The authors' aim in the present study was to discover the underlying dynamics of local (foot, hip, or head) and global (center of mass) components involved in balance control and how those dynamics are affected by changes in the available information. Participants ($N = 6$) had to maintain their balance on an unstable platform. Using dimensional analyses (largest Lyapunov exponent and correlation dimension), the authors examined the active degrees of freedom involved in balance control. Results indicated a similarity in dimension between local (joints) and global (center of mass) components, between a fixed point and a limit cycle. The behavior of the center of mass was found to be more predictable than the behavior of its local constituents. In addition, the available visual information affected the predictability of the postural behavior, which suggests that vision is used in the stabilization of the low-dimensional dynamics underlying balance control.

Key words: balance control, degrees of freedom, dimensionality

What the active degrees of freedom (*df*) are that humans and other animals produce when interacting with their environment is a central question for theories of movement coordination and control (e.g., Bernstein, 1967). The maintenance of an unstable equilibrium exemplifies the problem of compressing a state space of many local (i.e., muscular, segmental) dimensions into a state space of fewer (macroscopic) dimensions in order to maintain the center of mass above the feet and achieve suprapostural performances. If balance control is to be successful (as it almost always is), then the degrees of freedom of the body must be organized or coordinated so as to promote functional control actions and avoid dysfunctional ones. Bardy and colleagues recently formulated a dynamical account of pattern formation in the multisegmental control of stance. According to that account, postural states behave like attractors in the postural space and changes between states behave like self-organized, nonequilibrium phase transitions between attractors (e.g., Bardy, Marin, Stoffregen, & Bootsma, 1999; Bardy, Oullier, Bootsma, & Stoffregen, 2002). In those experiments, standing participants were instructed to move so as to maintain a constant distance between their head and a visual target that oscillated along the line of sight. They were exposed to stepwise changes (increasing or decreasing) in the frequency or amplitude of target motion, a manipulation that affected the existence of, and the transitions between, postural states. Two coordination modes between ankles and hips were found to emerge out of the interplay of intentional, behavioral, and environmental constraints: an in-phase (ankle–hip relative phase ϕ_{rel} of about 20°) and an antiphase (ϕ_{rel} close to 180°) mode. A frequency-induced loss of stability occurred as target frequency increased or decreased, yielding critical fluctuations in the vicinity of the transition region. An abrupt transition was observed between modes, with in-phase to antiphase transitions occurring at a higher target frequency than antiphase to in-phase transitions (hysteresis). Finally, both modes were found to be less stable when an external perturbation (a visual shift in the direction of the target) was applied close to the transition region than when it was applied far from it, as evidenced by larger relaxation time values in the latter situation.

Generally, those results offer converging evidence for the existence of self-organized phenomena operating at the level of whole-body coordination and encourage further examination of the possibility that the interactions between the various components of the postural system might be

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Correspondence address: Benoît G. Bardy, Research Center in Sport Sciences, University of Paris Sud XI, Batiment 335, 91405, Orsay, France. E-mail address: benoit.bardy@staps.u-psud.fr addressed through the physics of nonequilibrium processes. In this contribution, we pursue the dynamical account of posture and suggest that the coordination and control of unstable equilibrium develop upon functional, united, low-dimension actions. We argue that regularities expressing that dimensional reduction in the phase space of the movement can demonstrate the regulation of a small number of degrees of freedom at a macroscopic level. We report an experiment in which participants had to coordinate the various segments of their body in order to maintain their balance on an unstable platform. Using operational methods to assess the active *df* involved in movement coordination, known as *dimensional analyses* (e.g., Kay, 1988; Mitra, Amazeen, & Turvey, 1998; Newell, Challis, & Morrison, 2000), we aimed at discovering (a) the underlying dynamics of local (foot, hip, or head) and global (CM) components involved in balance control and (b) how those dynamics are (differentially) affected by changes in the available information.

Method

Participants ($N = 6$) were asked to maintain their balance on a stabilometer (Lafayette Instruments, Lafayette, IN; Model 16020). The 60-cm × 40-cm platform had its axis of rotation 20 cm above foot level and its maximal angular rotation was ±16° with regard to the horizontal axis. Participants stood on the platform in a comfortable Romberg position, with their shoulders perpendicular to its axis of rotation and their arms in the back (Figure 1). They were instructed to minimize the movement of the platform during a trial and to do their best to avoid contact of the platform's edges with the ground surface. Three vision conditions were tested. In the control condition, vision was available and no particular instructions were given to the participants. In the looking condition, participants were instructed to fixate a red target (1.5 cm × 1.5 cm) located at eye level 2.5 m from the platform. In the no-vision condition, the balance task was performed blindfolded. Each participant received eight experimental trials in each condition, presented in a random order. Trial duration was 30 s.

The motion of body segments was recorded in three dimensions at a sampling rate of 60 Hz with a five-camera VICON 370-2 (Oxford, England) infrared motion analysis system. Fifteen passive-reflecting markers were positioned on various parts of the body (left and right shoulders, sternum, left and right hips, left and right thighs, left and right knees, left and right tibias, left and right ankles, and left and right toes); we later computed from the obtained data the lateral position and motion of the left foot, hip, and head as well as the position and motion of the center of mass (CM) by using the biomechanical

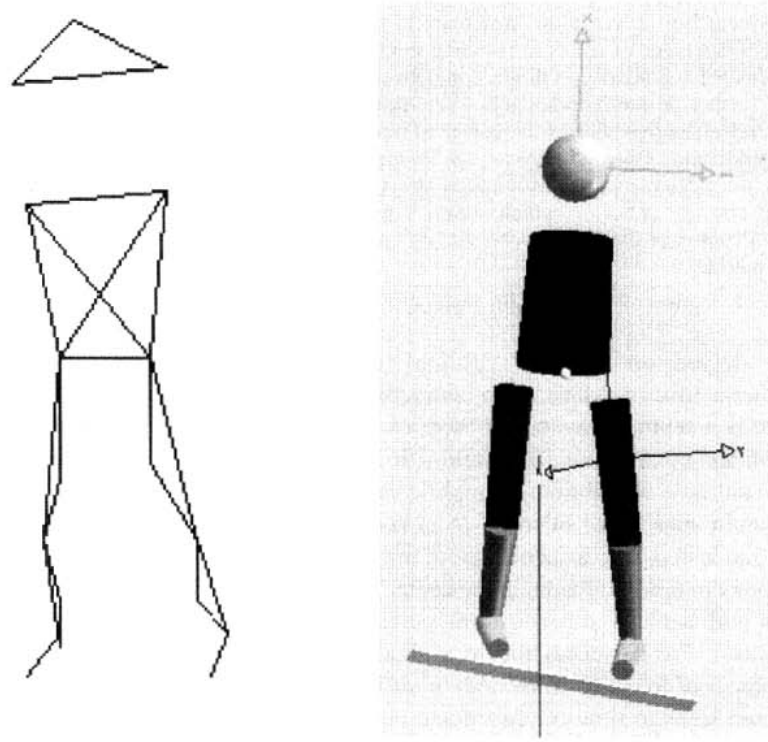

FIGURE 1. Experimental apparatus and biomechanical model: Stick figure of the task and assessment of center of mass (CM) position on the basis of the Chandler et al. (1985) biomechanical model.

model of Chandler, Clauser, McConvile, Reynolds, and Young (1985). In each trial, phase space reconstruction was applied at each of those levels, and the following four variables were computed for local (foot, hip, and head) and global (CM) components: (a) the standard deviation of lateral position at each level (*LV*), which assesses the relative stabilization of joints and CM in that direction; (b) the embedding dimension (*ED*), which measures the maximal size of each trajectory in the phase space; (c) the largest Lyapunov exponent (λ), which assesses the predictability of the time series behavior; and (d) the correlation dimension (*CD*), which captures the periodic, chaotic, or stochastic nature of the system under consideration. In addition, we computed the total duration of contact with the ground (DoC) per trial. Contacts were difficult to prevent and could be of different frequencies and durations in the three experimental conditions. For that reason, we computed the duration of each contact from two markers (left and right) pasted onto the stabilometer and added all values so that we would have an index of the total duration of contact per trial.

By using the algorithm developed by Kantz and Schreiber (1997), we calculated *ED*, which refers to the number of axes of a return map (the plot of a time series as a function of the current and of the previous values) sufficient to describe the properties of the corresponding phase space. We computed λ by using the algorithm of Wolf, Swift, Swinney, and Vastano (1985). Briefly, λ will be zero for a fully deterministic (predictable) system and infinite for a random (unpredictable) system. A negative value of λ reflects the existence of a stable fixed point, and a positive value of λ indicates the presence of chaos. Thus, λ quantifies the predictability of the system, in units of inverse time, and gives a time scale for divergence ($\lambda > 0$) or convergence ($\lambda < 0$) of nearby trajectories. We used the algorithm of Grassberger and Procaccia (1983) to compute *CD*. *CD* is the slope of the $\log(C[R]) - \log(R)$ linear regression, where $C(R)$ is the correlation integral of the time series. A *CD* of 1 (a two-dimensional system) implies a periodic or quasi-periodic attractor. Higher integer dimensions reveal indeterminate, stochastic systems. Noninteger *CD*s greater than 1 ($2 + \varepsilon$ dimensions) are characteristics of chaotic systems (strange attractors). We used a correlation coefficient of .8 between the $\log(C[R]) - \log(R)$ plot and the slope of the linear regression as a criterion to exclude unreliable estimates of *CD*.

To test for spurious effects, we computed similar dependent variables on surrogate data. The need for accurate statistical tests in nonlinear time series analysis and the usefulness of the Monte Carlo approach have been particularly stressed by Theiler, Eubank, Longtin, Galdrikian, and Farmer (1992). We transformed original data from the current study in the frequency domain by using a fast Fourier transform (FFT). Then, we multiplied the complex components by random phases uniformly distributed between 0 and 2π. We transformed the data back in the temporal domain by computing an inverse FFT. The resulting time series contained random numbers within the prescribed spectrum (Kantz & Schreiber, 1997) and was submitted to the same analysis.

ED, *LV*, and λ data were submitted to a 3 (vision: control, looking, no vision) × 4 (level: head, CM, hip, foot) multivariate analysis of variance (MANOVA), followed by two-way repeated measures ANOVAs on each of those variables. Because of the criterion used to exclude unreliable estimates values ($r \geq .8$), the number of *CD* values differed between conditions (see the following), and the effects of vision and level were analyzed in a separate ANOVA. Because the level variable for DoC was absent, duration of contact was also excluded from the general MANOVA and was analyzed separately.

Results

Data from one typical trial are illustrated in Figure 2, and means and standard deviations of the main dependent variables are shown in Table 1. Because of the criterion used to exclude unreliable fits, about 75% of the *CD* data were kept for analysis, yielding 100 (69%), 124 (83%), 111 (75%), and 104 (72%) trials at the level of CM, head, hip, and foot, respectively. The reliable trials were not differentially distributed among the conditions, $\chi^2(6) = 0.98$, *ns*.

The general MANOVA indicated a significant effect of vision, $R(6, 1{,}124) = 15.55$, $p < .05$, and level, $R(9, 1{,}367) = 422.61$, $p < .05$. The interaction between those two variables was also significant, $R(18, 1{,}590) = 7.67$, $p < .05$. We now describe the univariate analyses for each of the dependent variables.

Lateral Variability

Mean lateral standard deviation was 3.2 cm ($SD = 0.72$) at the CM level and was 11.07 cm ($SD = 1.88$), 1.11 cm ($SD = 0.34$), and 8.79 cm ($SD = 3.04$) at the level of the foot, the hip, and the head, respectively. Hence, the most immobilized joint in the environment was the hip, closely followed by the head. Foot and head components showed lateral movements of higher amplitude. The Vision × Level ANOVA performed on *LV* confirmed that result and showed a significant effect of level, $F(3, 564) = 1{,}390.49$, $p < .05$; moreover, all levels were significantly different from each other (post hoc Newman–Keuls, $p < .05$). The suppression of vision also affected *LV*, $F(2, 564) = 45.25$, $p < .05$; control ($M = 0.93$, $SD = 2.85$), looking ($M = 1.01$, $SD = 0.85$), and no vision ($M = 4.55$, $SD = 2.82$) were different from each other (Newman–Keuls, $p < .05$).

In addition, the interaction between vision and level was significant, $F(6, 564) = 22.05$, $p < .05$, suggesting that the suppression of vision predominantly increased the lateral movement of the head (see Table 1).

Embedding Dimension

ED was 2 in each trial of each condition. The Vision × Level ANOVA yielded no effect of vision, $F(2, 564) = 1$, *ns*,

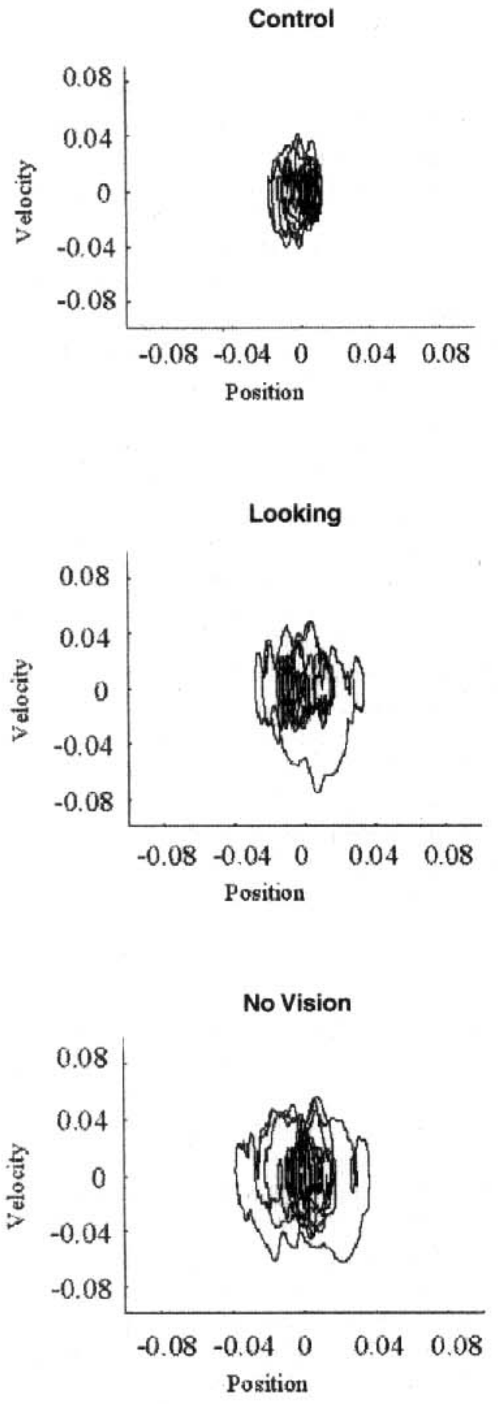

FIGURE 2. A typical trial illustrating a phase portrait of the (lateral) linear motion of the center of mass in the three visual conditions.

or level, $F(3, 564) = 1$, *ns*. That finding suggests that the geometry of the underlying dynamics was similar between conditions and did not exceed a limit cycle dynamics (see Figure 2).

TABLE 1
Means and Standard Deviations of Lateral Variability (*LV*), Largest Lyapunov Exponent λ, and Correlation Dimension (*CD*) for Lateral Motion of Center of Mass, Hip, Head, and Foot in Each Visual Condition

	LV (cm)		λ		*CD*	
Condition	*M*	*SD*	*M*	*SD*	*M*	*SD*
			CM			
Control	3.20	0.49	0.13	0.04	0.59	0.34
Looking	3.18	0.46	0.15	0.06	0.70	0.40
No vision	3.38	0.61	0.23	0.05	0.54	0.31
			Hip			
Control	0.98	0.44	0.57	0.20	0.45	0.32
Looking	1.07	0.45	0.62	0.92	0.48	0.32
No vision	1.27	0.52	0.66	0.25	0.50	0.35
			Head			
Control	7.00	2.83	1.70	0.61	0.57	0.43
Looking	5.73	2.85	1.49	0.46	0.55	0.38
No vision	9.86	3.39	1.98	0.76	0.48	0.27
			Foot			
Control	10.82	0.66	0.86	0.29	0.52	0.34
Looking	10.84	0.65	0.99	0.20	0.54	0.37
No vision	11.56	0.75	1.02	0.31	0.54	0.35

Largest Lyapunov Exponent

Lambda had a mean of 0.87 ($SD = 0.73$) across levels, conditions, and trials, suggesting a rather chaotic behavior of the postural system. There were important differences, however, between levels and conditions (see Table 1 for details). The Vision × Level ANOVA indicated a main effect for vision, $F(2, 564) = 15.22$, $p < .05$; the lateral movement of the body was more predictable when vision was available (looking and control conditions) then when it was not (no-vision condition), Newman–Keuls, $p < .05$. There was also a main effect for level, $F(3, 564) = 498.35$, $p < .05$, with all levels being significantly different from each other, Newman–Keuls, $p < .05$. A proximodistal gradient was found, with lower values for proximal components (hip and CM) and higher values for distal components (head and foot). The interaction between the two variables was significant, $F(6, 564) = 4.68$, $p < .05$, and indicated that vision predominantly affected the head component (see Table 1); the behavior of the head was indeed found to be less divergent when vision was available than when it was not.

To test for spurious effects, we performed the same analysis on the surrogate values of λ. Values of surrogate λ increased toward unpredictability, with means of 1.26 ($SD = 0.61$), 1.27 ($SD = 0.72$), and 1.30 ($SD = 0.65$), respectively, in the control, looking, and no-vision conditions. Surrogate values were different from the original values, $t(143) = 5.34$, $p < .05$. In addition, the Vision × Level ANOVA indicated no significant effect for vision or for level, both $Fs(6, 564) < 1$. Those results thus suggest the adequacy of dimensional analysis for assessing the presence of chaos and indicate that the (changing) dynamical behavior observed for the postural system in various conditions was not the consequence of the analyses used.

Correlation Dimension

CD had a mean of 0.53 ($SD = 0.35$) across levels, conditions, and trials. It did not differ between vision conditions, $F(2, 426) = 1.83$, *ns*, or levels, $F(3, 426) = 2.38$, *ns*, suggesting that the underlying attractor was of low dimensionality in each case, between a fixed point and a limit cycle attractor.

CD was also computed on the surrogate data and compared with the original values. Similar to what was found for λ, there was a significant increase in dimension for the surrogate data, with means of 0.86 ($SD = 0.42$), 0.85 ($SD = 0.37$), and 0.87 ($SD = 0.61$), respectively, in the control, looking, and no-vision conditions. Original and surrogate values of *CD* differed, $t(84) = 5.65$, $p < .05$. The Vision × Level ANOVA did not show any significant effect, all $Fs(6, 421) < 1$.

Taken together, those results suggest that the observed values of λ and *CD*, with the differences between vision conditions and levels, were attributable to the underlying dynamics of the postural system and not to a potential artifact introduced by the dimensional analyses.

Duration of Contact With the Ground

DoC was 0.93 s in the control condition, 1.01 s in the looking condition, and 4.55 s in the no-vision condition. A one-way ANOVA performed on DoC revealed a significant effect of vision, $F(2, 141) = 66.03$, $p < .05$, indicating that number or duration of contacts (or both) were not homogeneously distributed. A post hoc Newman–Keuls test indicated that DoC was significantly higher in the no-vision condition than in the other two conditions ($p < .05$). That result is not surprising and confirms the classical role of vision in the control of balance (e.g., Edwards, 1946). At the same time, it could be the case that DoC affected the dynamics of posture and that a difference in DoC between visual conditions was the cause of a difference in λ or *CD* between those visual conditions. That was, however, not the case, for there was a difference for λ but not for *CD*.

Discussion

Although a similarity in dimension was observed between local (joints) and global (CM) components of the postural system, the dynamical behavior of the CM was found to be more predictable than the behavior of its local constituents. In addition, the available visual information affected the predictability of the postural behavior at the head level but not the dimension of the underlying attractor.

The similarity in the values of *CD* at global and local levels (between 0 and 1) suggests that the behavior of the postural system oscillated between a fixed point and a limit cycle. That low-dimensional dynamics expresses the regulatory process underlying the maintenance of balance as well as the constraints acting upon the postural system. However, the differential values of λ between local and global levels suggest a more predictable behavior at the global level (CM) than at the local levels (foot, hip, or head). That finding is consequential for theories of postural control that focus on the role played by segmental stabilization in the regulation of stance (e.g., Massion, 1992; Nashner, Shupert, Horak, & Black, 1989; Pozzo, Berthoz, Lefort, & Vitte, 1991). Those theories indeed suggest that the position of a stabilized segment can provide a reference frame for the organization of the movement. The most stabilized segment in the present study was the hip joint (*LV* of 1.11 cm across visual conditions). However, the value of the largest Lyapunov exponent for that joint indicated chaotic behavior, with a mean λ of 0.62 (across visual conditions), the reciprocal of which yielded a short estimation of the predictable time for that segment. On the other hand, the dynamic behavior of the CM can be predicted on a larger time scale, although its absolute lateral motion was higher than that of the hip. Those results indicate that there is not a one-to-one mapping between the predictability of the postural system's behavior and the absolute motion of its constituents and that its stability is not necessarily to be found at the level of joint motion. However, the finding that the absence of vision mostly affected the predictability and motion of the head's behavior suggests that the head plays a crucial role in modulating the postural dynamics.

Whether it is possible to develop a general theory of postural control while taking into account the co-existence of those observations remains an open question, which may be addressed in future research. For the present, we believe that the present results should encourage examination of the relationship between the local and the global dynamics underlying the maintenance of unstable equilibrium as well as the role played by perceptual information in stabilizing those dynamics.

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REFERENCES

Bardy, B. G., Marin, L., Stoffregen, T. A., & Bootsma, R. J. (1999). Postural coordination modes considered as emergent phenomena. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 1284–1301.

Bardy, B. G., Oullier, O., Bootsma, R. J., & Stoffregen, T. A. (2002). The dynamics of human postural transitions. *Journal of*

Experimental Psychology: Human Perception and Performance.

Bernstein, N. (1967). *The co-ordination and regulation of movement.* London: Pergamon Press.

Chandler, R. F., Clauser, C. E., McConvile, J. T., Reynolds, H. M., & Young, J. W. (1975). *Investigation of inertial properties of the human body* (Tech. Rep. AMRL-TR-137, NTIS No AD-AO16 485). Wright-Patterson Air force Base, OH: Aerospace Medical Research Laboratories, Aerospace Medical Division.

Edwards, A. S. (1946). Body sway and vision. *Journal of Experimental Psychology, 36,* 526–535.

Grassberger, P., & Procaccia, I. (1983). Measuring the strangeness of strange attractors. *Physica D, 9,* 189–208.

Kantz, H., & Schreiber, T. (1997). *Nonlinear time series analysis.* Cambridge, England: Cambridge University Press.

Kay, B. A. (1988). The dimensionality of movement trajectories and the degrees of freedom problem: A tutorial. *Human Movement Science, 7,* 343–364.

Massion, J. (1992). Movement, posture, and equilibrium: Interaction and coordination. *Progress in Neurobiology, 38,* 35–56.

Mitra, S., Amazeen, P. G., & Turvey, M. T. (1998). Intermediate motor learning as decreasing active (dynamical) degrees of freedom. *Human Movement Science, 17,* 17–66.

Nashner, L. M., Shupert, C. L., Horak, F. B., & Black, F. O. (1989). Organization of posture control: An analysis of sensory and mechanical constraints. *Progress in Brain Research, 80,* 411–418.

Newell, K. M., Challis, S., & Morrison, S. (2000). Dimensional constraints on limb movements. *Human Movement Science, 19,* 175–201.

Pozzo, T., Berthoz, A., Lefort, L., & Vitte, E. (1991). Head stabilization during various locomotor tasks in humans. II. Patients with bilateral peripheral vestibular deficits. *Experimental Brain Research, 85,* 208–217.

Theiler, J., Eubank, S., Longtin, A., Galdrikian, B., & Farmer, J. D. (1992). Testing for nonlinearity in time series: The method of surrogate data. *Physica D, 58,* 77.

Wolf, A., Swift, J. B., Swinney, H. L., & Vastano, J. A. (1985). Determining Lyapounov exponents from a time series. *Physica D, 16,* 285–317.

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