Neuroscience Letters 452 (2009) 37–41

Contents lists available at ScienceDirect

Neuroscience Letters

journal homepage: www.elsevier.com/locate/neulet

Delayed visual feedback reveals distinct time scales in balance control

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ARTICLE INFO

Article history:
Received 31 October 2008
Received in revised form
29 December 2008
Accepted 8 January 2009

Keywords:
Postural control
Visual feedback
Center-of-pressure

ABSTRACT

We performed an experiment in which we challenged postural stability in 12 healthy subjects by providing artificial delayed visual feedback. A monitor at eye-height presented subjects with a visual representation of the location of their center-of-pressure (COP) and they were instructed to position their COP as accurately as possible on a small target. Visual feedback of the COP was displayed either in real-time, or delayed by 250, 500, 750, or 1000 ms. In a control condition, no visual feedback was provided. As expected, stability increased during real-time visual feedback compared to when feedback was absent. To identify time scales at which postural control during quiet stance takes place we sought to distinguish between different frequencies. Low frequencies, i.e. slow components of postural sway, showed a monotonic increase in sway amplitude with increasing delay, whereas high frequencies, i.e. fast components of postural sway, showed significantly reduced sway amplitude for delays of 500–750 ms compared to the other delay conditions. Low- and high-frequency components of postural sway thus exhibited differential susceptibility to artificial delays, thereby supporting the notion of postural control taking place on two distinct time scales.

With the body center-of-mass (COM) located a fair distance above the ground and supported only by two multi-jointed segments, muscular control is critical to maintain upright posture as evidenced by the fact that even quiet standing is never truly steady. To prevent falling the COM's vertical projection has to stay within the base of support formed by the two ft. How can humans realize these challenging, dynamical adjustments without having specialized sensory receptors detecting the body's COM position? If quiet standing were solely controlled by muscle tone, as has been suggested in the context of modeling quiet stance as inverted pendulums, one would expect sway not to be influenced by afferent input to the CNS [8,27]. However the effects of various feedback contributions described in the literature suggest otherwise [15,21,25]; moreover, the information these feedback systems provide is not redundant as maximal reflex gain requires them all [6]. Removing or corrupting one or more types of sensory information hence provides a means to disentangle its relative contribution under given circumstances. One such perturbation, well-known for its capacity to either stabilize or destabilize dynamical systems, is (additional) time-delayed feedback [20]. In motor control this has been demonstrated for instance in speech [13] and oculomanual tracking [26]. For the latter, deleterious effects of time-delayed feedback range from simple fixed point shifts via spontaneously emerging oscillatory patterns to unstable (or running) solutions. Put differently, not only can delays result in a loss of accuracy and stability, the appearance of distinct dynamical regimes upon variation of this delay also provides a striking example of the complex behavior that nonlinear systems with (multiple, negative) feedback loops can produce [2,17]. For postural control, such a rich spectrum of responses to this type of feedback manipulation has not been examined, probably because instability simply implies falling. However, recent research by Rougier has shown that properly chosen time-delayed visual feedback tends to have stabilizing effects on balance [22,23].

Body sway patterns are typically analyzed by means of the (temporal) statistics of the center-of-pressure (COP), the point location of the vertical ground reaction force vector as derived from force platform data. Interestingly, numerous studies on COP time series have repeatedly reported evidence for the existence of processes that take place on two distinct time scales [1,5,7,28]. For instance, Collins and De Luca [5] showed that over short-term (<1 s) and long-term (>1 s) intervals the COP may behave as a persistent and anti persistent random walk, respectively. These findings were taken as indicative of distinct control regimes: on a short time scale the system would be allowed to 'drift' and the resulting deviations would be suppressed by restoring forces acting on a larger time scale. In contrast, a dual system describing one level of control that sets the

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doi:10.1016/j.neulet.2009.01.024

reference point and another that stabilizes posture around the reference has also been suggested [14,28]. The latter process is taking place on a much faster time scale than the relatively slow process of reference point updating. On a more practical level, the COP signal has been shown to follow the movements of the COM, oscillating on either side of it, suggesting that the slow, i.e. low-frequency, dynamics of the COP signal can be attributed to the movements of the relatively large inertial mass of the body [27]. Correlates of the fast, i.e. high-frequency, dynamics of postural sway are less clear-cut but are assumed to involve feedback control in which the postural response required to stabilize an inverted pendulum is determined by both a 'stiffness' factor and a 'damping' factor [12,19]. As it stands, however, our understanding of the integration of multi-modal sensory information subserving postural control is far from complete.

To probe the dynamics of upright standing we used time-delayed visual feedback of the COP trajectory. The questions we sought to answer in this study were: (a) will behavior destabilize (entirely) at a certain delay; (b) will there be a delay at which balance becomes more stable; and (c) by modifying the delay, can we distinguish between slower, more sustained components of postural sway and components that evolve more rapidly? With this study we built on earlier findings of Rougier [23] that indicated that the overall decrease in postural sway under the influence of artificial visual feedback of the subjects' COP is due to reduced motions of the COM, but this is accompanied by an increase in the difference between COP and COM vertical displacement (COP–COM_v), a parameter proportional to the horizontal acceleration communicated to the COM. Rougier also showed that visual feedback of the COP delayed over 300, 600, 900, and 1200 ms tends to have stabilizing effects on the COP–COM_v parameter, whereas the COM motions remained largely unaffected [22]. Therefore we expected that upon the proper distinction between fast and slow components of postural sway the high-frequency components (∼COP–COM_v) would exhibit a decrease under conditions of delayed visual feedback while the low-frequency components (∼COM_v) would increase.

Six male and six female subjects who reported no known balance deficits, visual impairments, or neurological disorders participated in this study that was carried out after approval from the University of Ottawa's Institutional Research Ethics board.

COP data during quiet standing were collected under five visual feedback conditions plus one control condition. Subjects were asked to stand on a 600 mm × 400 mm force plate (Kistler 9281B) in a comfortable position with their arms relaxed alongside their body. An LCD-monitor (frame rate of 25 Hz) placed 70 cm from the force plate at eye-height presented subjects with a visual representation of their COP location (Ø4 mm). Subjects were instructed to position their COP as accurately as possible within a fixed target circle (Ø10 mm) on the screen. After two practice trials with instantaneous visual feedback, subjects completed five blocks containing six randomized trials (one trial for each of six conditions). Trials lasted 31 s, the first second of which was implemented to accommodate the delay (see below) and hence not used for data analysis. Subjects were given a short break in between trials. Visual feedback of the COP was displayed either in real-time or delayed by 250, 500, 750, or 1000 ms.[1] In the control condition, visual feedback of the COP was withheld and only the target circle was shown. For this condition, subjects were instructed to focus on the center of the target and to stand as still as possible.

Force plate data were sampled at a frequency of 1000 Hz and COP coordinates along anterioposterior (AP) and mediolateral (ML) axes were calculated on-line, stored, and displayed (LabView, National Instruments). Target circle location was computed as the mean location of COP during the initial 1000 ms of each trial. This period was also used to buffer COP data so that the appearance of the visual display could always be triggered at 1000 ms after the beginning of the trial. COP time series along both AP and ML axes were analyzed (Matlab 7.0, Mathworks, Natick, MA) across a range of filter settings. Standard deviations of the COP along both axes were calculated after low- or high-pass filtering the data using a second-order bi-directional Butterworth filter.[2] This procedure is equivalent to the one used by Rougier, who estimated motions of the COM via low-pass filtering of the COP; as such the parameter COP–COM_v consists of the difference between COP and low-pass filtered COP and thus represents high-pass filtered COP [3,22,23]. We analyzed a wide range of cut-off frequencies ($f_{\text{cut-off}}$) from 0.1 to 1.0 Hz to determine what frequency would yield a proper discrimination between slow and fast components of postural sway; this frequency served as the cut-off frequency in our further analyses. To minimize transient effects, all trials in the first block were discarded. After filtering, residual linear trends and DC-values of the time series were removed. For each trial the mean standard deviation in AP and ML was calculated and subsequently normalized with respect to each subject's mean standard deviation over the last four trials in the no-feedback condition. Effects of delay conditions were analyzed using a repeated measures ANOVA with *feedback* (no feedback, real-time feedback, and feedback at 250, 500, 750, and 1000 ms delays) as within-subjects factor (see footnote 2). Separate analyses were conducted for the four measures formed by combining the two filters and two axes (low-AP, high-AP, low-ML, and high-ML). If sphericity could not be assumed the Huynh–Feldt correction was applied. For significant main effects we applied post hoc tests for multiple comparisons using Bonferroni-corrected confidence intervals to ensure a family-wise confidence level of 95%.

All subjects were able to perform the required task, although delay conditions visibly affected the accuracy of marker positioning within the target area. Under increasing delay oscillations around the equilibrium position were observed as well as a concomitant increase in amplitude. Due to pronounced transient effects, the first six trials for each subject were discarded prior to data analysis.

Effects of different $f_{\text{cut-off}}$ of high- and low-pass filters on the variability along both the AP and ML axes are summarized in Fig. 1. Low-pass filtering of the signal along the AP axis at very low $f_{\text{cut-off}}$ resulted in a very strong reduction in the normalized standard deviation. The standard deviation increased with increasing $f_{\text{cut-off}}$, i.e. with increasing presence of higher frequency components. This effect was visible across all feedback conditions and along both AP and ML sway axes. High-pass filtering showed an altogether different trend with the highest mean standard deviations for low $f_{\text{cut-off}}$, and smaller (mostly decreasing) values for higher $f_{\text{cut-off}}$, i.e. a reduced impact of low-frequency components. To distinguish between low- and high-frequency domains, an $f_{\text{cut-off}}$ of 0.3 Hz was chosen as upon a visual inspection this appeared to yield representative and discriminative results; cf. also [12].

For the low-pass filtered data we observed a stepwise increase under the influence of delay as sketched in Fig. 2, which displays the mean standard deviation along the AP axis normalized to the no-feedback condition for unfiltered (center panels) as well as filtered data (low-pass, left panels, and high-pass, right panels, $f_{\text{cut-off}} = 0.3$ Hz). On average deviations in the 0 ms and the 250 ms condition were reduced compared to the no-feedback condition,

[1] Due to digitization there was an additional lag of about 50 ms as revealed by high-speed video recordings.

[2] Filtering and subsequent computation of the standard deviation over time equals the integration of the spectral power over corresponding frequency intervals. For example, instead of the low-pass filtering we alternatively could have integrated the power spectra up to the cut-off frequency and taken the square root of that integral; note that we did not apply statistical tests to determine the 'optimal' cut-off frequency.

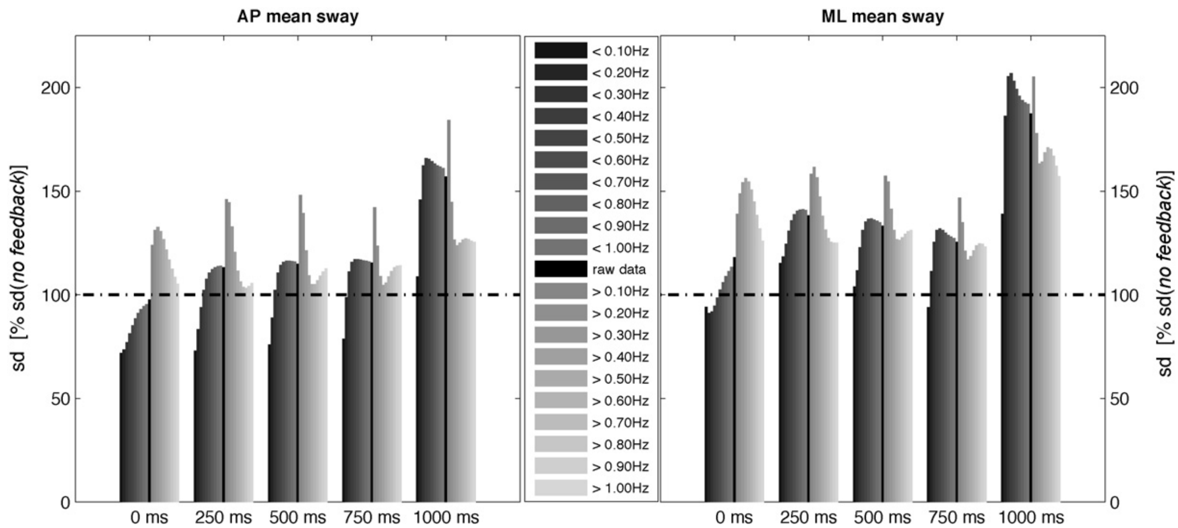

Fig. 1. Effects of different cut-off frequencies ($f_{\text{cut-off}}$) on the normalized standard deviation. Low-pass filtering (darker bars, e.g., '<0.50 Hz') of the signal along the AP axis (left panel) at very low $f_{\text{cut-off}}$ showed very strong reduction in standard deviations, whereas high-pass filtering (lighter bars, e.g., '>0.50 Hz') at similar $f_{\text{cut-off}}$ showed a strong increase in standard deviations; black bar represents unfiltered data. Results for the ML axis (right panel) show similar trends as results for the AP axis.

indicating a clear influence of visual information on the slower components of postural sway. A marked increase was found for a delay of 1000 ms. High-pass components of sway had higher mean standard deviations relative to the no-feedback condition for all conditions. No clear trend was observed for high-pass filtered data. We note that conditions of relatively short (250 ms) and relatively long delays (1000 ms) displayed increased deviation; delays of 500 ms and, especially, 750 ms showed decreased deviations. For the ML axis the trends mirrored to a large extent the results for the AP axis. Major difference was that along the former axis variability between participants was much greater, suggesting that not every subject responded by using the same strategy. But again, a 'dip' was observed for high-pass filtered data at 750 ms.

Statistical analysis yielded significant effects of delay for low-pass filtered AP data ($F(2.56, 28.17) = 12.40$, $p < .005$, Huynh–Feldt correction) and for low-pass filtered ML data ($F(1.56, 17.17) = 4.97$, $p < .05$, Huynh–Feldt correction). High-pass filtered data did not show significant results for either AP or ML data. Post hoc com-

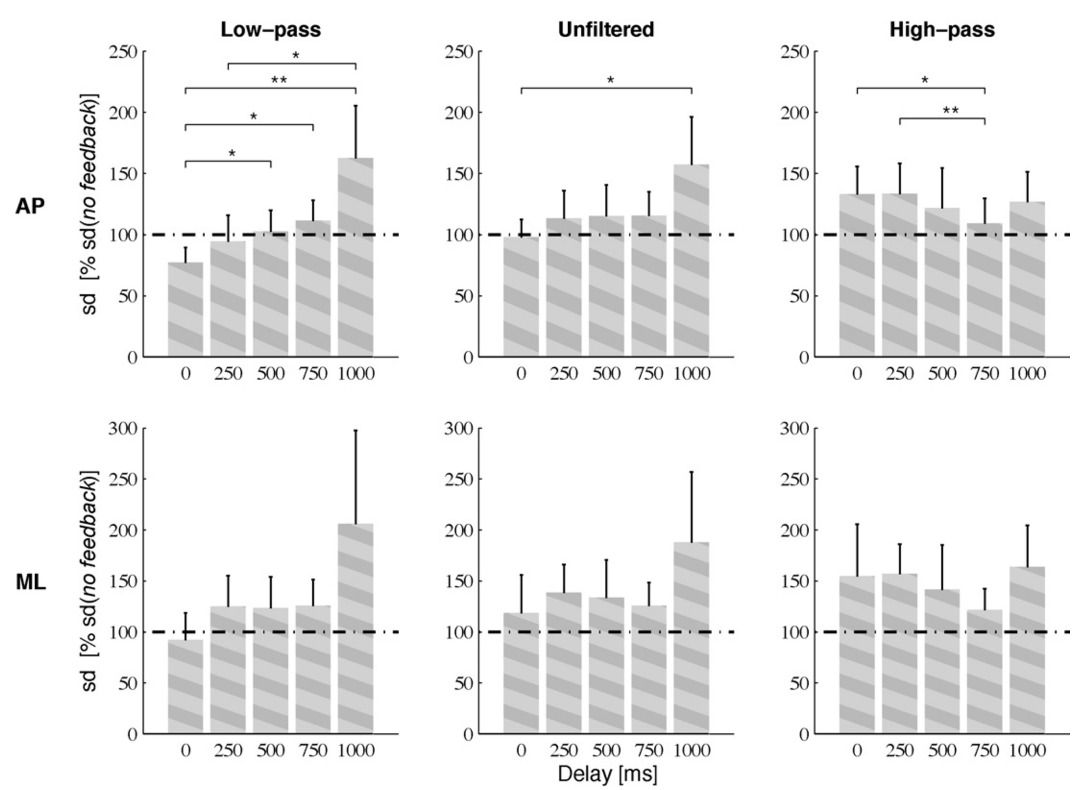

Fig. 2. Mean standard deviation normalized to the no-feedback condition along both axes. Top row: AP; bottom row: ML. Left column: low-pass filtered data; right column: high-pass filtered data. Significant differences between conditions are indicated. 95% confidence intervals based on the standard error of the individual means are included in the graph; for correlated measurements standard errors of the individual means are always greater than standard errors of the difference that were used to calculate differences between within-subject means. For the ML axis no significant results were found. * $p < 0.05$, ** $p < 0.01$.

parisons revealed several significant results, summarized in Fig. 2. Pair-wise comparisons of low-pass filtered data along the AP axis (top left panel) revealed significant differences between 0 and 500 ms ($p = .024$), between 0 and 750 ms ($p = .011$), between 0 and 1000 ms ($p = .004$), and between 250 and 1000 ms ($p = .028$), for unfiltered data between 0 and 1000 ms ($p = .020$), and for high-pass filtered displacements (top right panel) between 0 and 750 ms ($p = .04$) and between 250 and 750 ms ($p = .005$). For the ML axis however, effects of delay were not significant for either filtered or unfiltered data.

Before summarizing the results we first recall the three central research questions that motivated our study:

(a) *Will behavior destabilize (entirely) at a certain delay?* Providing additional feedback of the COP location did not result in greater stability over all frequencies if this information had been delayed. That is, whereas *real-time* artificially enhanced visual information generally reduces deviations from a given point of reference, such feedback loses its hence beneficial effects on postural control if the additional information is not available to the CNS within a physiologically meaningful time. Along both the AP and ML axes, irrespective of filtering, delayed visual information appeared to destabilize the postural response when compared to the real-time visual feedback condition (Fig. 2). With greater delays the overshoot past the target increases in amplitude causing low-frequency oscillations which are accompanied by an increase in variability across subjects. Note that large, slow oscillations caused by the delayed visual information were only intermittently regular. As expected, standard deviation increased notably with the introduction of a delay. Interestingly, however, the added visual delay caused differential effects in low-pass and high-pass filtered COP signals, or slow and fast processes, respectively. Low-pass filtered data showed a monotonic increase as delay increased, with more than one and a half times as much deviation in the 1000 ms condition than in the no-feedback condition. Mean normalized variability for the high-pass filtered data was much higher for feedback conditions than for the control condition, but did not increase monotonically with delay. Together these results confirm the findings by Rougier who reported decreased variability of COP–COM_v motions under the influence of delay whereas COM movements increased [22]. A complete loss of stability was not observed for any of the subjects. Presumably the influences of sources of feedback other than the artificially delayed feedback on COP location were too strong to be ignored altogether.

(b) *Will there be a delay at which balance becomes more stable?* Although normalized mean standard deviations generally increased with increasing delay and were greater than those for the no-feedback condition, at a delay of 750 ms the high-frequency components of sway displayed a local minimum for AP and ML. On a global level this did not imply a direct stabilization as measured by normalized standard deviation (cf. unfiltered data in Fig. 2), but merely a maintenance of the values found for the 250 and 500 ms conditions for ML. In fact, along the AP axis the same step-wise increase for low-pass filtered data (Fig. 2, top left panel) was observed in reverse for high-pass filtered data up until delays of 750 ms (top right panel). This indicates comparable stability on the global level (top center panel) for 250, 500, and 750 ms, but with different relative contributions from low- and high-frequency components. A clear explanation for the reduced values at 500–750 ms and increasing values for both shorter and longer delays may not be readily formulated but we submit that coupling strength between the different sources of feedback and central corrective processes was influenced by the temporal disparity among these sources. This raises the question whether the system underwent a delay-induced, qualitative change, and if so, where exactly the change was taking place. Note that the reduced standard deviation for delays of 750 ms is again increased for delays of 1000 ms; this could indicate a critical point and a corresponding phase transition [11]. The notion of transitions between dynamical states calls for more advanced measures accounting for the stochastic dynamics of postural sway as well as models in which bifurcations can be induced [9,17]. Tass et al. [26] focused on the identification of distinctive dynamical regimes through the initiation of transitions from one state to another upon variations in delay size, there the so-called control parameter. One could hypothesize that above all the *interactions* between (a number of) subsystems would be responsible for the unexpected reduction in standard deviation in our experiment. For example, feedback might be deemed 'correct' by the CNS not only during sway trajectories in which the additional visual feedback is synchronous, or 'in-phase', with other forms of afferent information, but perhaps during an anti phase relationship of these components as well. Thus, decoupling or reweighing of feedback may depend on the period of the slow component of the sway trajectory [12]. The extent to which subjects were coupled – phase-locked – to the visual stimulus seemed to vary markedly, and may suggest that a number of different strategies is employed by the nervous system during quiet standing.

(c) *Can we distinguish between slower, more sustained components of postural sway and components that evolve more rapidly by modifying the delay?* Postural stabilization is effectively taking place on two time scales, in line with the aforementioned suggestions of fast and slow processes for balance control [1,5,7,28]. Thus, observing the differential susceptibility to delays as concerns filtered data, in our view the application of low- and high-pass filters is a sound method to tease apart the two time scales at play during postural stabilization (see footnote 2). Low-pass filtering yielded normalized standard deviations lower than 1, indicating greater stability for slow components with instantaneous feedback compared to without feedback. In this sense, high-frequency components are suspected to be the main contributors to the system's destabilization. The slow component seems to be largely dictated by the inertial properties of the oscillating mass of the subject. Fast oscillatory components of sway are more likely to represent the lump sum of irregular, voluntary and involuntary muscle activity and multisensory feedback integration [10]. Similar reasoning motivated Rougier in a very recent study to feed back not just the composite COP signal but also to present subjects with delayed information of either only COM movements or only the horizontal acceleration communicated to the COM [24]. Delayed visual feedback of the latter induced a reduction of its own variance accompanied by an increase in COM movements where feedback of only COM motions did not show any significant effects.

To protect a system against instabilities arising from delays only two control strategies appear feasible: intermittent and predictive control [16]. Intermittent control consists of movement interspersed with small pauses, allowing for a step-by-step evaluation of sensory information [18]. The observed monotonic rise of low-frequency components could be explained by a reduced gain in reaction to the detection of a corrupted source of information. In other words, information which is not representative of a subject's state may cause central processes to rely more heavily on alternative mechanisms that perform conservative (fewer and smaller) adjustments. Fewer adjustments could result in larger deviations and thus an increase in sway for the slow components. This seems to suggest a form of intermittent control in which refractory periods between movements allow time for veridical sensory feedback to be obtained [10]. Over the course of the experiment, most subjects seemed to 'discover' this strategy. Alternatively, employing a forward model allows for the outcome of an action to be approximated internally and this predictable, continuous feedback is then used to guide the movement [26]. If computational mechanisms assumed to take place in the CNS are not in some way adjusted to compensate for delays, the postural control system as a whole will have great difficulty in maintaining stability. Theoretical support for the implementation of forward models comes from the vast field of artificial neural networks in the form of Bullock and Grossberg's Vector-Integration-To-Endpoint- or VITE-model [4], in which motor performance does not depend critically on on-line feedback as information about the present position is also based on an efference copy of the issued motor command. The VITE-model has been successfully applied to postural control [7], aptly describing stochastic aspects of quiet standing [5].

In summary, our results showed that postural control was greatly affected by delays in visual feedback, and that these effects appeared for delays as small as 500 ms. In addition we observed that low- and high-frequency components of postural sway were subject to differential susceptibility to artificial delays, supporting the notion of postural control taking place on two time scales. We conclude that slow aspects of postural sway are due to inertial properties of the oscillating mass, while the fast oscillatory components of postural sway are more likely representing the lump sum of irregular, voluntary and involuntary muscle activity as well as the product of multisensory feedback integration.

Acknowledgments

International Creative Research Award (awarded to Ramesh Balasubramaniam, Andreas Daffertshofer, André Longtin, and Peter Beek); NWO grant (#452.04.344 awarded to Andreas Daffertshofer); NSERC discovery grant (awarded to Ramesh Balasubramaniam and André Longtin); Dutch Brain Foundation research internship grant (awarded to Maarten van den Heuvel).

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