Visuomotor tracking on a computer screen - An experimental paradigm to study the dynamics of motor control

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Abstract

In this work we propose a new experimental paradigm in the context of human motor control. Human subjects track a target with a mouse-pointer on a computer screen while the underlying dynamics is similar to a stick-balancing problem. This approach gives wide control over system parameters. We show that there are two scaling regions in the power spectrum of the distance r between mouse and target and find a power law in the laminar phases distribution of r. We propose a model for this dynamics and compare the model results to the experimental findings.

Key words: balancing, tracking, motor control

1 Introduction

Computational principles of human motor control like motor planning, estimation, prediction and learning have recently attracted much attention (e.g. [1]). A particular class of problems, the continuous feedback control, is especially suited to derive dynamical properties and mechanisms underlying the control of body movements. Examples for such feedback systems include the control of body posture [2] where noise-induced transitions between co-existing periodic orbits account for the dynamics of the body center-of-pressure [3]; and the problem of balancing a stick at the fingertip where the existence of parametric noise and on-off intermittency have been demonstrated [4]. These two systems, however, allow only for a limited manipulation of system parameters. In postural sway, body mass and height are basically fixed and in stick balancing, only the mass and the geometry of the stick can be altered deliberately. Here we introduce an experimental paradigm for the study of human motor control that allows for a more flexible variation of system parameters: The visually guided control of a target on a computer screen by moving a computer mouse. The reaction time of a human subject may be changed by an additional delay and even the whole dynamics of the system may be altered. This makes it possible to test models of the reaction against the change of those parameters.

2 Experimental setup

Subjects are presented two dots on a computer screen. The first dot m represents the position of the subject's hands and is controlled by the computer mouse. The second dot t is the target, which is to be balanced by the subject. The subject's task is to keep both dots as closely together as possible, while avoiding the escape of either point off the screen. The target moves according to $\ddot{\vec{x}}_t(t) = k\,(\vec{x}_t(t) - \vec{x}_m(t-\tau))$, where $\vec{x}_t(t)$ and $\vec{x}_m(t)$ are the positions of the target t and the mouse pointer m, respectively. t moves within a parabolic potential centered at the position of m. m is an unstable equilibrium position for t. k controls the strength of the potential. Increasing k will make it more difficult for the subject to solve the balancing task. τ is an additional delay on top of the subject's physiological delay. The basic additional delay was set to 2 ms to allow for computer processing time, which is variable and would not be accounted for in a 0 ms-delay setup. During a balancing session the movements of both m and t are recorded with a sample rate of 100 Hz. While moving the mouse in an area of one quarter of the screen size, the subjects can cover the whole screen area with the mouse pointer. (The balancing performance of the subjects was much lower when the area in which to move the mouse was of the same size as the screen.) The subject begins a balancing experiment by pressing a key when ready. Each session starts with t and m in mid-screen. Both points are separated by only one pixel to induce an initial movement to which the subject reacts. The experiment ends when one point escapes off the computer screen, and the subject may start another experiment. A whole session lasts about half an hour. The number of experiments accomplished during a session therefore depends on the subject's ability to balance.

3 Results

Under this experimental paradigm subjects produce balancing trajectories as shown in Figure 1. In Figure 2 the distance $r = |\vec{x}_t - \vec{x}_m|$ between m and t is shown. There are regions where m closely tracks t. In other regions, where t is on the verge to escape, larger and faster movements of m are necessary and the distance r becomes larger.

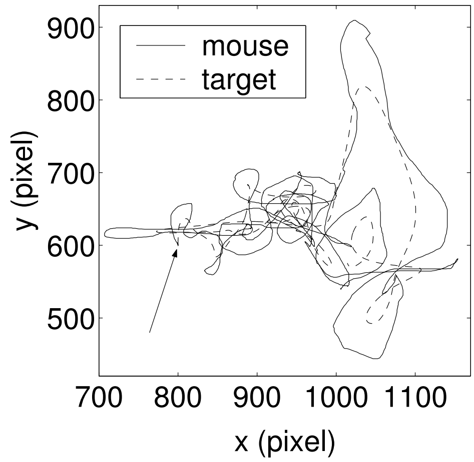

Fig. 1. Balancing trajectories m and t of a 32-year-old male subject. The units are in pixels. The area shown is a part of the 1200×1600 pixel computer screen. Starting point indicated by arrow. $k = 10$, $\tau = 2$ ms.

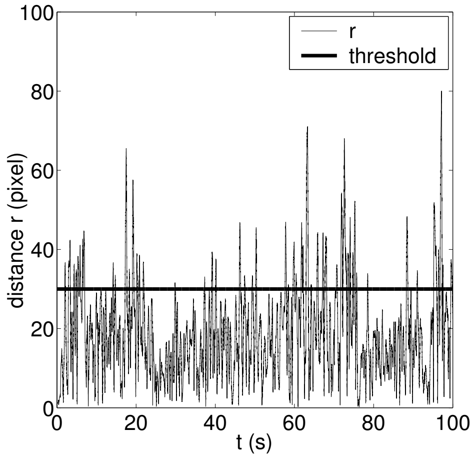

Fig. 2. Balancing sequence of a 32-year-old male subject. The graph shows the distance r between mouse and target as a function of time t. $k = 10$.

This behaviour is also reflected in the power spectrum of r Figure 3. Nine balancing sequences were accumulated to produce this powerspectrum. The powerspectrum clearly shows to scaling regions, with two different power laws. In the frequency range of 10^{-2} Hz to 1 Hz, the power spectrum is governed by a power law with exponent -0.6 (dashed line). Between 1 Hz and 100 Hz the power law shows an exponent of -2.5 (solid line). The diminishing slope near 100 Hz is due to the finite sampling. This behaviour was also found in stick balancing experiments [4], where it was interpreted as a sign for on-off intermittency [5].

By introducing a suitable threshold for r at 30 pixels on the screen (Fig. 2, horizontal line), we distinguish between time intervals when mouse pointer and target are close and time intervals of larger distance. We can then determine the length of the time intervals between adjacent crossings of the threshold (corrective movements). These time intervals are referred to as laminar phases. Figure 4 shows a log-log plot of the distribution of the lengths of the laminar phases. A power law with slope $-\frac{3}{2}$ is visible. Deviations at large laminar phases are expected because of the limited amount of data, deviations at small laminar phases are due to white noise. The behaviour matches that of 3-dimensional stick-balancing [4].

In this experimental paradigm there are naturally occuring delays, namely the physiological delay of the visuomotor system. To estimate this delay, we

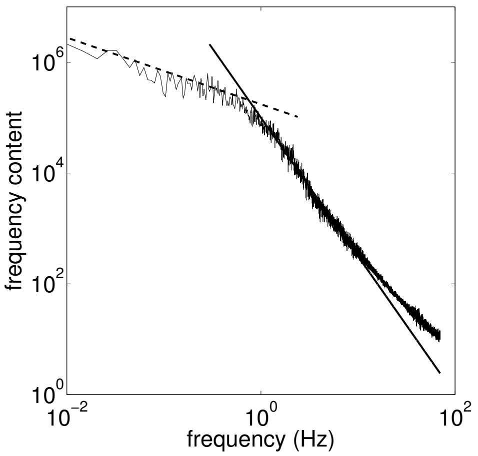

Fig. 3. Powerspectrum of r for several accumulated balancing sequences of a 32-year old male subject. $k = 10$, $\tau = 2$ ms.

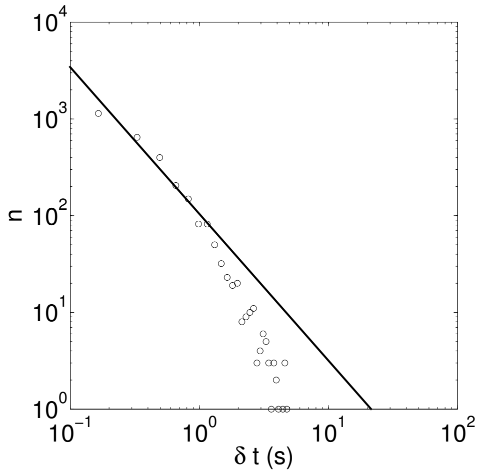

Fig. 4. Log-log-plot of the laminar phases distribution of the balancing sequences of a 20-year-old male subject, accumulated over several trials. $k = 20$.

calculated the variance of the acceleration $a_m\,(t + \tau)$ for various distances $r(t)$. The delay τ for which $\mathrm{var}(a_m)$ was minimal was than averaged over all occurring r. Thus we found the delay to be about 340 ms for one subject.

One feature of this experimental paradigm is the possibility to introduce additional arbitrary delays τ. The subject's ability to balance showed a fast decline with larger additional τ [6]. Delays of about 150 ms reduces the balancing time from 200 s at $k = 10$ to a few seconds. In some cases, subjects were able to produce sufficiently long balancing sequences to compute the total delay. The results showed that the additional delay was added to the natural delay as was expected.

4 A model with parametric noise

As a simple model for balancing as in the experiment, i. e., the movement of target and mouse, we propose the following:

The target moves according to the same equation as in the experiment. The target is modelled as an inverted pendulum with respect to the suspension point: $\ddot{\vec{x}}_t\,(t) = k\,(\vec{x}_t\,(t) - \vec{x}_m\,(t))$. The reaction of the subject to a movement of the target away from the equilibrium is modelled by a restoring force $\vec{F}_r\,(t - \tau_r)$. The reaction has a delay τ_r that is consistent with the reaction time of a human subject: $\ddot{\vec{x}}_m\,(t) = \vec{F}_r\,(t - \tau_r)$. We assumed a force $\vec{F}_r\,(t - \tau)$ that is linear in the distance r between mouse and target: $\vec{F}_r\,(t - \tau_r) =$

$\vec{\xi}(t)\, b\,(\vec{x}_t\,(t-\tau_r) - \vec{x}_m\,(t-\tau_r))$. The parametric noise term is important for balancing [4].

With this approach, the balancing sequence and powerspectrum in figures 5 and 6 are obtained. The model reproduces the two scaling regions in the power spectrum. The power laws have different slopes: -1.1 in the left region and -2.1 in the right region. The critical point lies at the same location.

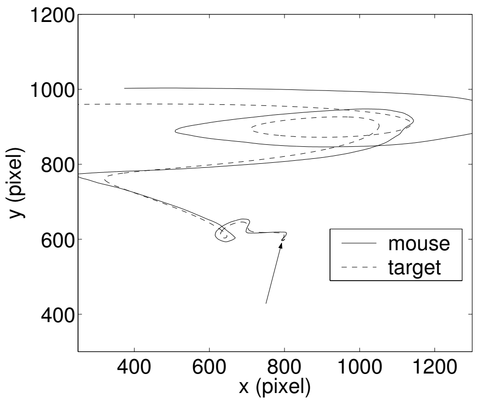

Fig. 5. Balancing trajectories m and t generated by the model. The units are in pixels. The area shown is a part of the 1200×1600 pixel computer screen. Starting point indicated by arrow. $k = 10$, $b = 15$, $\tau_r = 20$ ms

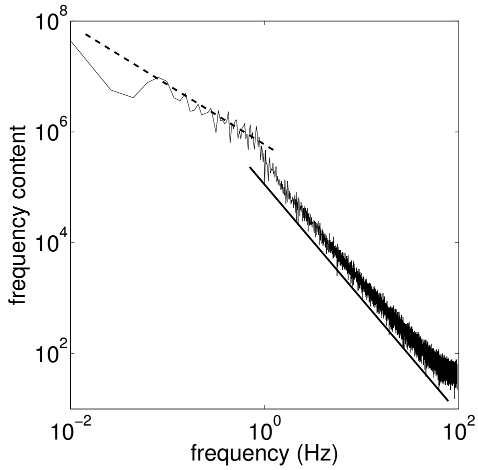

Fig. 6. Log-log-plot of the powerspectrum for several accumulated model balancing sequences. $k = 10$, $b = 15$, $\tau_r = 20$ ms. Straight lines shifted for visibility.

5 Conclusion

Here we have shown a flexible experimental paradigm which can add to the understanding of balancing and related problems. We have shown some important features of the experimental data, as the double power law in the power spectrum and the power law in the laminar phases distribution. A simple model accounts for the two scaling regions in the power-spectrum. An improved model should increase both the balancing time and τ to more realistic values. The parameter τ exists in real balancing experiments and it is important to analyze its impact on models for balancing. This is not possible with other experiments that study balancing. A comparison with stick balancing in three dimensions shows that the statistics of the movement are similar. Further investigations will reveal, if it also resembles the behaviour of other motor control systems such as the control of human upright stance – which might hint at common motor control schemes.

References

[1] D. Wolpert and Z. Ghahramani, *Computational principles of movement neuroscience* Nature Neurosci. Suppl. **3** (2000) 1212–1217.

[2] J. J. Collins and C. J. De Luca CJ, *Open-loop and closed-loop control of posture: a random walk analysis of center-of-pressure trajectories*, Exp. Brain Res. **95** (1993) 308–318.

[3] C. W. Eurich CW and J. G. Milton, *Noise-induced transition in human postural sway*, Phys. Rev. E **54** (1996) 6681–6684.

[4] J. L. Cabrera and J. G. Milton, *On-off intermittency in a human balancing task*, Phys. Rev. Lett. **89** (2002) 158702.

[5] S. C. Venkataramani, T. M. Antonson Jr., E. Ott and J. C. Sommerer, *On-off intermittency: power spectrum and fractal properties of timeseries*, Physica D **96** (1996) 66–99.

[6] I. S. MacKenzie and S. Ware, *Lag as a determinant of human performance in interactive systems*, Proceedings of the ACM Conference on Human Factors in Computing Systems - INTERCHI (1993) 488–493.

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