Sinusoidal Visuomotor Tracking: Intermittent Servo-Control or Coupled Oscillations?

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ABSTRACT. In visuomotor tasks that involve accuracy demands, small directional changes in the trajectories have been taken as evidence of feedback-based error corrections. In the present study variability, or intermittency, in visuomotor tracking of sinusoidal targets was investigated. Two lines of analyses were pursued: First, the hypothesis that humans fundamentally act as intermittent servo-controlers was re-examined, probing the question of whether discontinuities in the movement trajectory directly imply intermittent control. Second, an alternative hypothesis was evaluated: that rhythmic tracking movements are generated by entrainment between the oscillations of the target and the user, such that intermittency expresses the degree of stability. In 2 experiments, participants (N = 6 in each experiment) swung 1 of 2 different hand-held pendulums, tracking a rhythmic target that oscillated at different frequencies with a constant amplitude. In 1 line of analyses, the authors tested the intermittency hypothesis by using the typical kinematic error measures and spectral analysis. In a 2nd line, they examined relative phase and its variability, following analyses of rhythmic interlimb coordination. The results showed that visually guided corrective processes play a role, especially for slow movements. Intermittency, assessed as frequency and power components of the movement trajectory, was found to change as a function of both target frequency and the manipulandum’s inertia. Support for entrainment was found in conditions in which task frequency was identical to or higher than the effector’s eigenfrequency. The results suggest that it is the symmetry between task and effector that determines which behavioral regime is dominant.

Key words: intermittency, perception-action coupling, rhythmic movements, servo-control, tracking

A common observation in many types of movements is that underlying the superficial smoothness of behavior there are small rapid changes in endpoint trajectory. That observation has been made in a number of different task situations and can be traced back at least a century. As early as 1899, Woodworth investigated line-drawing tasks and reported irregularities in the lines participants drew just before they homed onto the target. He interpreted that feature as the signature of a corrective, or current control phase that reduces errors in a number of discrete steps and is separate from an initial transport or ballistic phase. As the trajectory approaches the target, the actor samples, intermittently, the remaining error to the target and implements proportional corrections to nullify the error. Since the study by Woodworth, such discontinuities have been observed in a wide spectrum of tasks and have become a focus of investigation to gain insight into the nature of the control processes underlying the generation of voluntary movements. For discrete aiming movements to small targets, discontinuities have been reported in the velocity trace, in contrast to the typically claimed smooth bell-shaped velocity profile (Meyer, Abrams, Kornblum, Wright, & Smith, 1988; Meyer, Smith, Kornblum, Abrams, & Wright, 1990).

Those changes in velocity have been interpreted as a parsing of the aiming movement into submovements or different “strokes.” The implication of that interpretation is that the movement is not planned in its entirety, at least not when there are visually presented accuracy demands. A class of movement tasks in which the issue of corrective, that is, closed-loop, control has been the primary focus of interest is visuomotor tracking. Since the 1950s, that task has received considerable interest, which was initially motivated by its applicability to the design of ergonomically efficient control implements (Wickens, 1984). The objective of the investigators who have employed that paradigm in numerous studies until now has been to elucidate fundamental aspects of the motor control system. In a seminal
study, Craik (1947) observed that when participants followed moving targets, tracking errors included directional changes at a frequency around 2 Hz, irrespective of the frequencies contained in the target trajectory. He interpreted that finding as intermittent corrections by a central controller. Couched in the conceptual framework of control theory, the view is that a positional mismatch between target and pursuit is sensed by the visual system and is fed back to the processing center, which issues corrections. The challenge for the theorist is to draw conclusions about the nature of the control unit, that is, the transfer function characterizing the human controller (Hammerton, 1981; Miall, 1995).

Intermittent changes in the tracking trajectory have been demonstrated in many variations of visuomotor tracking tasks, ranging from completely predictable to random targets and testing various display and control properties (Poulton, 1974; Vince, 1947; Weir, Stein, & Miall, 1989; Wickens, 1984). More recently, Miall, Weir, and Stein (1993), for instance, reported intermittent corrections in the velocity trace of joystick movements at frequencies between 0.5 and 1.5 Hz in addition to the primary frequency of the tracked target. In the visuomotor tracking literature, those directional changes, typically concentrated within a limited band of frequencies (other than the primary target frequency for periodic targets), have been termed intermittency (Vince, 1947).

In the literature on visuomotor tracking, a number of possible explanations have been proposed for intermittency; those explanations include an internal clock that controls the timing of the actor’s corrective responses (Bekey, 1962), a psychophysiological refractory period that delays the production of the next response (Smith, 1967; Vince, 1947), and an error deadzone around the target within which no adjustments are detected or deemed necessary (Wolpert, Miall, Winter, & Stein, 1992). Central to all these interpretations of intermittency is the view that humans are intermittent servo-controllers (Craik, 1947; Miall et al., 1993; Neilson, Neilson, & O’Dwyer, 1988; Neilson, O’Dwyer, & Neilson, 1988; O’Dwyer & Neilson, 1998; Poulton, 1974; Weir et al., 1989). It is assumed that the fundamental nature of human movement control is discrete and that all movements are a concatenation of submovements. The notion that complex movements are a sequence of simpler movements, or strokes, has also received support from observations of discontinuities in the movement trace of participants attempting to produce curves with constant curvature (Abend, Bizi, & Morasso, 1982; Viviani & Terzuolo, 1980).

Recently, Sternad and Schaal (1999) readdressed the issue of stroke-based control by assessing segmentation in the endpoint trajectory of humans who were producing drawing movements in three dimensions. Piecewise planarity in three-dimensional (3D) drawing movements has been suggested as the signature of segmentation in 3D movements (Soechting & Terzuolo, 1987). Participants could faithfully reproduce the apparent segmentation by using only continuous oscillations in the seven joint degrees of freedom of the arm. The results demonstrated that the apparent segmentation of endpoint trajectories arises from the nonlinear transformation between joint and end-effector profiles. Hence, discontinuities in the endpoint trajectory do not necessarily imply segmented control. That finding raises our awareness that caution should be used in drawing inferences from the kinematics of the end-effector trace directly to control processes occurring at another level in the system. Our first hypothesis is that intermittency in the kinematics may reflect underlying causes other than intermittent control. Specifically, as developed further later on, we tested the hypothesis that stability properties in the dynamics of the target–effector system determine the degree of fluctuations.

In the literature on intermittency, no one has provided a rigorous definition of the term, mainly because the nature of the discrete control steps varies depending on task and biomechanical factors. Four different task-related sources of intermittency can be identified: First, the degree of intermittency has been found to be dependent on the predictability of target motions. Whereas in tracking unpredictable targets, participants must react to unexpected changes with a delay, their responses are smoother when repetitive targets such as sinusoidal waves are tracked (Miall et al., 1993). Second, the amount of practice leads to a reduction in the signs of intermittency, both in pseudo-random and sinusoidal target motions (Miall et al., 1993; Noble, Fitts, & Warren, 1955). Third, manipulation of visual information alters the degree of intermittency. Removing online visual feedback of the actor’s response or even the target motion altogether leads to a reduction in intermittency (Miall et al., 1993). Fourth, intermittency is reduced when target frequency or velocity is increased, specifically in sinusoidal targets (Noble et al., 1955), when discrete movements are produced at different constant velocities, and when different ellipses produced by different target velocities are traced in phase space (Doeringer & Hogan, 1998). In aiming movements, intermittency decreases with increasing movement speed (Woodworth, 1899). In summary, the degree of intermittency changes with the task dimensions.

Previously, such changes in the degree of intermittency have not been regarded as a problem for the intermittent control hypothesis (although, see criticism in Hammerton, 1981). Instead, researchers have captured changes in the degree of intermittency with certain task properties by using additional parameters and loops in the transfer function (Miall, 1995). The decrease in intermittency with more regular target motions has been described as additional predictive mechanisms that anticipate the target’s movements. With practice, such anticipatory processes are further enhanced. Intermittency without the presence of visual feedback has been ascribed to error corrections based on other perceptual information, including memory representation of the target. Increasing intermittency with the addi-
tion of visual information has been attributed to the more accurate or salient error information. The observation that intermittency decreases with increasing target velocity or frequency has been attributed to the fact that at faster movement frequencies the actor is less able to make reversals in the movement. The last point suggests that mechanical properties of the effector or the manipulandum may influence the actor’s ability to make changes in the movement trajectory.

The contribution of mechanical properties of the control manipulandum has been investigated in several studies in which the researchers’ objective has been to determine the ideal manipulandum for an ergonomic design. For instance, Howland and Noble (1955) investigated different control devices, typically joysticks with combinations of spring resistance, viscous damping, and inertia. The general conclusions from that work and other studies are that such control devices with loading are less accurate in tracking performance (see also Bahrnick, Bennett, & Fitts, 1955; Notterman & Page, 1962). Within the control-theoretical framework, mechanical properties of the system are viewed as part of the plant that the controller, that is, the central nervous system, directs (see Figure 1). The controller typically captures the dynamic properties of the plant in the order and time delay of the transfer functions in order to produce the observed gain and phase lag. The controller either has to compensate for those properties in a predictive fashion, using an internal model of the plant, or has to overcome occurring lags or errors by making corrections. Specifically, without feedforward control, increasing the moment of inertia of the manipulandum leads to a greater phase lag behind the target signal, which the controller has to overcome by making increased corrections. With anticipatory control based on internal models, the task imposes additional processing demands on the operator. In research on visuomotor tracking, investigators have typically used lightweight joysticks in an attempt to attenuate the influence of mechanical properties on the output, both to better elucidate the control processes and to develop optimal ergonomic designs (Doeringer & Hogan, 1998; Poulton, 1974).

A different emphasis on the role of mechanical properties has been advanced in the ecological and in the dynamic systems approaches. In those theoretical perspectives, it is emphasized that behavior results from the interplay of the actor embedded within a task, where mechanical or dynamical properties of both actor and environment are salient in constraining the behavior (Figure 1; for more discussion, see Warren, 1998). That is, mechanical properties of the system are given prominence not only in shaping the output but also in providing important constraints and possibilities to be exploited for control and coordination (Bernstein, 1967; Newell, 1986). One line of research in which the important role of oscillating mechanical systems has been demonstrated is the wrist–pendulum paradigm of Kugler and Turvey (1987). Investigators ask participants to swing pendulums of varying length and mass constituting different eigenfrequencies in order to investigate the influence of physical properties on the behavior. In the bimanual coordination task of swinging nonidentical pendulums in each hand, investigators have found that asymmetry in the eigenfrequencies of each pendulum leads to systematic phase lags between the two pendulums’ trajectories (Schmidt, 1993; Sternad, Amazeen, & Turvey, 1996; Sternad, Turvey, & Schmidt, 1992). Important for the present argument is the finding that when the asymmetry between the two pendular effectors is increased, fluctuations in the endpoint kinematics are also increased. The fluctuations arise from internal perturbations or noise in the system that increases for less stable movement regimes. That interpretation of variability differs from the view that intermittent changes are the result

![Figure 1](https://example.com/figure1.png)

of explicit error corrections imposed by the controller. In
other words, we hypothesize that the observed intermit-
tency in visuomotor tracking may be the expression of sta-
\( \text{bility} \) and variability of a dynamical system.

Although that conceptual contrast provides a helpful
organizing framework for the present analyses, a word of
cautions is necessary: Over the past decades, the contro-
sersy between the dynamic systems and the control-theoretical
approach has driven much of the research in movement
\( \text{science} \) but has at times exaggerated and aggravated the
differences. More recently, for instance, Pressing (1998, 1999)
demonstrated that when a sufficiently general analytic
framework is adopted, the formal models of both approaches
\( \text{can} \) be transformed into one another. Yet, the opposition
remains one of emphasis and is more conceptual than formal
\( \text{for a discussion of the term \text{dynamics} in the context of} \) control
theory, see Jordan, 1996).

Coupled oscillator models have predominantly been
applied to interlimb coordination, including the movements
of two fingers, wrists, wrist–pendulums, or legs and arms
together (for overviews, see Amazeen, Amazeen, & Turvey,
1998; Kelso, 1995). Specifically, the success of the so-
called Haken-Kelso-Bunz model (Haken, Kelso, & Bunz,
1985) has gained support from the finding that not only
mechanically coupled systems but also systems with no
mechanical linkage, such as two people or a limb and a per-
ceptual target, can be accounted for in the same model
\( \text{(Amazeen, Schmidt, \& Turvey, 1995; Byblow, Chua, \&} \)
Goodman, 1995; Kelso, Delcolle, \& Schönner, 1990;
Schmidt, Carello, \& Turvey, 1990; Wimmers, Beek, \& van
Wieringen, 1992). For instance, Kelso et al. (1990) investi-
gated rhythmic single-finger movements synchronizing or
synchronizing with an auditory metronome. A loss of sta-
\( \text{bility} \) of the synchronizing mode that induced a transition to the
\( \text{synchronizing mode was interpreted as the signature of} \) coupled oscillations in a perception–action task. In the same
\( \text{vein, Wimmers and colleagues used a visuomotor tracking} \)
paradigm in which participants tracked a sinusoidally mov-
ing light-emitting-diode target by using single forearm
\( \text{movements. Results showed a phase transition from} \) antiphase to in-phase coordination and a loss in stability of the
antiphase pattern as target frequency was increased.
\( \text{Those results demonstrated that visual and auditory track-
} \) ing can be considered as entrainment; the target and the
\( \text{movement system can be modeled as coupled oscillators.} \)
\( \text{Note that only phase transitions were looked at in those} \)
\( \text{studies, and steady-state behavior was not analyzed.} \)

In the present experiment, we examined the issue of
intermittency in a rhythmic visuomotor tracking task and
tested the interpretation of action and perception as
\( \text{entrained oscillations. To that end, we used the wrist–pen-
} \) dulum task in which participants swing hand-held pendu-
lums, tracking sinusoidally moving targets while receiving
\( \text{online feedback information about the tracking manipu-
} \) landum. The mechanical properties of the manipulandum were
\( \text{experimentally controlled so that they had different eigen-} \)
frequencies. Major issues of concern were the following:
\( \text{Can fluctuations in the trajectory be interpreted as intermit-
} \) tent control, that is, a concatenation of discrete strokes, or
\( \text{should rhythmic tracking be viewed as continuous entrain-
} \) ment between oscillations? Are the fluctuations a function of
\( \text{the compatibility, or symmetry, between task and actor} \)
\( \text{where mechanical characteristics influence the nature of the} \)
task–effectors system? Can intermittency be interpreted as a
\( \text{signature of stability of a dynamic system? We addressed} \)
\( \text{those questions by quantifying the variability or intermit-
} \) tency at different target frequencies and pendulum eigenfrequen-
cies, following two lines of analysis.

**EXPERIMENT 1**

**Method**

**Participants**

Six volunteers (4 men and 2 women, mean age = 32.1 ±
6.8 years) from The Pennsylvania State University partici-
pated in this study. According to self-report, 4 participants
were right-hand dominant and 2 were left-handed. All
reported normal or corrected-to-normal eyesight. Three of
the participants had prior experience with the task. They all
agreed to the experimental procedures by signing the
\( \text{informed consent form required by the University Regula-
} \) tory Committee.

**Apparatus and Materials**

Participants sat in a specially built chair and placed their
\( \text{forearms on the horizontal armrests provided. They grasped} \)
a pendulum in their dominant hand and swung it in the
\( \text{sagittal plane (see Figure 2). To record the pendulum’s} \)
\( \text{movement trajectory, we used a Sonic 3-Space Digitizer} \)
\( \text{(SAC Corporation, Stratford, CT) that recorded the sounds} \)
\( \text{made by an emitter attached to the bottom of the pendulum.} \)
The sound was detected by three of the four microphones
\( \text{arranged in a square on the floor (77 cm × 77 cm); the worst} \)
\( \text{readings were eliminated. The sampling rate was 60 Hz.} \)
The chair had a full leg rest and was attached to one side of
\( \text{an enclosure; because of that arrangement, the chair did not} \)
\( \text{have any support that obscured the sound from the} \)
\( \text{emitter on the pendulum to the four microphones. We covered} \)
\( \text{the sides of the enclosure and the underneath of the chair with} \)
\( \text{sound-proofing material (eggcrate foam) to reduce the pos-
} \) sibility of reflection errors. Armrests were provided so that
\( \text{participants could swing the pendulums only by using wrist} \)
\( \text{abduction or adduction and so that the position of the pen-
} \) dulum would be standardized.}

Participants swung one pendulum in their dominant
\( \text{hand. Two pendulums of different eigenfrequencies} \)
\( \text{were used: (a) a 33-cm-long pendulum with 20-g weight} \)
\( \text{attached, giving an eigenfrequency of 1.2 Hz (7.58 rad/s),} \)
\( \text{and (b) a 48-cm-long pendulum with both 200-g and 50-g} \)
\( \text{weights attached, giving an eigenfrequency of 0.8 Hz (5.02} \)
\( \text{rad/s). The calculations of the pendulums’ eigenfrequencies} \)
\( \text{included the mass of the pendular components (wooden} \)

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332 Journal of Motor Behavior
handle, aluminum rod, and steel weights) and the mass of the hand (0.6% of body mass), with all components modeled as hollow cylinders. On the basis of the center of mass and equivalent length of the compound system oscillating around the axis of rotation at the wrist, we determined the eigenfrequency by following standard algorithms (more details are described in Sternad, Collins, & Turvey, 1995; Kugler & Turvey, 1987; see also Note 1). We chose pendulum eigenfrequencies that were distinctly different from each other. A limiting factor for the choice was potential fatigue of participants when using the long and heavy pendulum; for the small pendulum, a limiting factor was sufficient length to enable us to obtain good digitizer readings.

From the raw position data in three Cartesian dimensions, we calculated the angular displacement of the pendulum's tip around the axis of rotation in the wrist by using custom-written motion analysis software; the result was stored on a Master Computer 486 DX 266 PCI. The target movement and the pendulum's tracking movement were visually displayed on an Acerview 7155 monitor situated in front of the participant (1.50 m from the back of the chair) and approximately in line with the participant's eye level. The monitor screen was 1.20 m from the participants' eyes, although their head position was not constrained. We dimmed the lights to enhance the contrast of the visual display on the screen. A hollow target square (1 × 1 cm) moved in a sinusoidal motion in only the vertical direction on the monitor, making a visual angle of 0.5° (0.0082 rad). The movements of the pendulum's tip, which were displayed as a green cross (1 × 1 cm) on the monitor screen, represented the participant's pendulum angular position. The refresh rate of the monitor was 60 Hz. The cursor was constrained to move in the same vertical direction on the monitor as the target square, corresponding to pendular movements in the sagittal plane. Pendular movements in the frontal plane were not shown to limit the attentional demands on the participant. The cursor appeared only during actual data collection. Thirteen different frequencies \( \omega_{P} \) of target oscillation were used: 0.1 to 1.3 Hz in 0.1-Hz increments. The upper limit was determined by

the refresh rate and the fact that the limiting frequency for smooth pursuit eye movements is 1.5 Hz, with best pursuit around 1 Hz (Leist, Freund, & Cohen, 1987). We chose the lower limit to obtain comparability with other studies. The peak-to-valley amplitude of the sine wave was kept constant at 0.52 rad for all frequency conditions, creating a vertical movement of 11.6 cm on the screen and a visual angle of 5.4° (0.095 rad) at the eye.

Procedure and Design

Participants were instructed to match the movement of the target on the screen by swinging the pendulum in the sagittal plane, trying to keep the cross in the target square. Throughout the experiment, participants were required to maintain their forearms on the armrest and to grasp the pendulum firmly so that no movement could occur within the hand. The task was always performed with the dominant hand. For left-handers, we displaced the screen display to the left to match the spatial arrangement to the one seen by the right-handers. Trials lasted 40 s; we provided 5-s lead-in time during which only the target was moving on the screen to allow the participants to find the target before data was collected. Two testing sessions were performed over 2 days, with no more than 48 hr between sessions. Two blocks of trials were performed each day, one block with each pendulum. The order of presentation of each pendulum was randomized across participants, with the order switched on the 2nd day. Each block consisted of a total of 13 trials, 1 at each frequency, the order of which was randomized. On each testing day, 5 practice trials were given; participants used the same pendulum as was used in the first session of the experimental trials. The five target frequencies \( \omega_{T} \) for the practice trials were 0.1, 0.4, 0.7, 1.0, and 1.3 Hz and were presented in random order. Participants could rest between trials if necessary to avoid fatigue.

Data Reduction and Dependent Measures

We low-pass filtered the time series of the pendulum's angular position for each trial by using a zero-lag second-order Butterworth filter with a cutoff at 8 Hz. Using a two-time step differentiation, we computed the angular velocity. The first 3 s of each time series were excluded from the analysis because they were confounded with transient effects. We determined average cycle measures of the time series of the pendulum angular position by using custom-written motion analysis software. Means and standard deviations of the peak-to-peak period \( T_{P} \) were calculated, along with mean, standard deviations, and constant error of peak-to-valley amplitude \( A_{P} \). We computed further measures by using software written in MATLAB. We quantified positional accuracy of the tracking performance by determining the root mean square error (RMSE) for the whole time series.

To analyze the participant's performance in the frequency domain, we computed the power spectrum of the pendulum's angular velocity. The velocity signal was preferred to
the position signal because it enhances directional changes in
the trajectory. Using Welch's averaged periodogram method, we estimated the power spectral density. We divided
the angular velocity time series into nine sections of 512
samples overlapping by 256 samples by using a Hanning
window, and we zero padded the result to 2,048 samples.
The resolution of the power spectrum was .029 Hz. Because
the movement velocity increases with higher target frequen-
cies and the power at the spectral peaks is proportional
to the amplitude of the signal, we normalized the velocity
signal by dividing the pendulum's angular velocity by the
target frequency. Variables derived from the power spec-
trum were power and frequency of the primary peak. The
primary peak was defined as the frequency at the largest
power in the spectrum.

The tracking trajectory contained one dominant frequency;
the spectral power concentrated at that frequency over-
shadows power associated with other frequencies that are of
primary interest when one determines the presence of inter-
mittent directional changes in the trajectory. Therefore, we
took two more routes to assess power at lower amplitude
frequencies. First, a sinewave was fitted to the pendular
position trace, which was subsequently subtracted. The
residual time series was differentiated, and the same spec-
tral analyses were performed as were described earlier. A
method for extracting a mean frequency coordinate that rep-
resents the location of maximal spectral power is the calcu-
lation of center-of-gravity COG measures (Foulkes &
Miall, 2000). The advantage of those measures is that for a
spectrogram with a broader distribution of power, where the
peaks are not invariantly defined at demarcated frequencies,
the spectrum is reduced to two parameters, f_{COG} and P_{COG}.
They are calculated as follows:

\[
\begin{align*}
    f_{COG} &= \frac{\sum_{i=1}^{n} f_i p_i}{\sum_{i=1}^{n} p_i}, \\
    P_{COG} &= \frac{\sum_{i=1}^{n} f_i p_i}{\sum_{i=1}^{n} f_i}
\end{align*}
\]

where \(f_i\) is the frequency and \(p_i\) is the power at the \(n\)th data
point of the frequency range. The range over which that
measure was calculated was between 0 and 8 Hz. Because
the frequencies are uniformly sampled, the calculation of
\(P_{COG}\) can be reduced to

\[
P_{COG} = \frac{\sum_{i=1}^{n} p_i}{n}
\]

Another set of dependent measures was determined in
phase space, that is, the space spanned by angular position
and velocity. A first step in computing measures in phase
space is to mean adjust the angular position by subtracting
the average pendulum position. We normalized the angular
velocity by dividing the velocity signal by the target fre-
quency. For the normalized phase portrait, the phase angle
of the pendulum, \(\theta_p\), was determined as the arctangent
of the mean adjusted position and normalized velocity time
series (for more detail, see Sternad et al., 1996). We calcu-
lated the radius \(p\) by using Pythagoras's theorem. To cap-
ture the variability of the trajectory in comparison with a
smooth harmonic wave, we computed a measure called Har-
monicity \(H\). After calculating the average radius \(p\) for the
whole cycle, that mean was subtracted from the time series
of \(p\). (A harmonic wave is characterized by a perfect circle
in phase space after normalization of velocity.) The remain-
er was summed like an RMSE, capturing the difference
between the trajectory's limit cycle and a harmonic wave.
Consequently, \(H\) is zero for a perfect harmonic wave, and it
increases with departures from a harmonic wave (for more
detail, see Sternad, Turvey, & Saltzman, 1999).

The primary dependent measure of coordination between
tracking and the tracked target is continuous relative phase
\(\psi\). To that end, we also computed the phase angle of the tar-
get oscillations \(\Theta_t\) in analogous fashion as for the pendu-
lum. To calculate \(\psi\), we applied circular statistics (Burgess-
The continuous time series of \(\psi\) was calculated as follows:

\[
\begin{align*}
    C_i &= \cos(\theta_{p,i} - \theta_{t,i}), \\
    S_i &= \sin(\theta_{p,i} - \theta_{t,i}), \\
    \psi_i &= \tan^{-1}(S_i / C_i),
\end{align*}
\]

where \(i\) denotes the samples. To obtain mean relative phase
\(\psi\) per trial, we averaged the \(x\) and \(y\) coordinates as follows:

\[
\begin{align*}
    \bar{C} &= \frac{1}{n} \sum_{i=1}^{n} C_i, \\
    \bar{S} &= \frac{1}{n} \sum_{i=1}^{n} S_i.
\end{align*}
\]

where \(n\) is the total number of samples per trial. The corre-
sponding measure of dispersion on the circle was

\[
R = (\bar{C}^2 + \bar{S}^2)^{1/2}.
\]

Because that measure varies between 0 and 1, where 0 cor-
responds to highest dispersion, \(R\) is converted to a linear
measure of uniformity \(D\psi\) varying between 0 and infinity
according to

\[
D\psi = (-2 \log, R)^{1/2}.
\]

Because the dispersion estimate captures variability only
in a time-independent fashion, we also performed a spectral
analysis on the continuous relative phase in order to scruti-
inize for temporal features in the fluctuating signal of rela-
tive phase. Therefore, the quantities \(f_{COG}\) and \(P_{COG}\), intro-
duced earlier, were calculated for relative phase.

Last, the difference between the target frequency and the
eigenfrequency of the pendulum was captured in the so-
called detuning parameter \(\delta\), computed as the arithmetic
difference between the pendulum eigenfrequency and target
frequency: \(\delta = \omega_p - \omega_t\).

We analyzed each dependent variable separately, using a
two-way repeated measures analysis of variance (ANOVA) with two levels of pendulum and 13 levels of target frequency. In instances of violations to the assumption of sphericity, we adjusted the degrees of freedom by using the correction factor epsilon computed according to the Huynh-Feldt method (Girden, 1992). In analyses on phase space measures, standard regression techniques were used.

Results and Discussion

Cycle Period and Amplitude

In Figure 3A, B, and C (left panels) are shown the time series of the pendulum’s and the target’s angular positions from a representative participant who was tracking three different target frequencies by using the faster (1.2 Hz) pendulum. It can be readily observed that participants accurately produced the correct peak-to-peak period $T_p$ for all target frequencies. That result was supported by the finding that $T_p$ changed significantly with target frequency, $F(1, 19, 5.96) = 4133.01, p < .001$. No interaction or main effect of pendulum and target frequency was found. The errors in $T_p$ were small, ranging from 1 ms to 7 ms, and no systematic drift in the periods was observed. That finding indicates that participants were able to overcome the different inertial properties of the pendulums with eigenfrequencies of 1.2 and 0.8 Hz to produce the wide range of target frequencies from 0.1 to 1.3 Hz. For an overview of those and the following cycle results, see Table 1.

Although $T_p$ was accurately achieved, there were differences in the variability across conditions. Standard deviations $SD(T_p)$ showed a decrease as the target frequency was increased, $F(1, 16, 8.00) = 14.65, p < .005$. As with the mean $T_p$, the pendulum variable failed to significantly influence the variability of $T_p$.

In Figure 3, the error in peak-to-valley amplitude $A_p$, also referred to as gain, can be discerned. The mean $A_p$ was significantly affected by an interaction between target frequency and pendulum, $F(8, 40) = 2.57, p < .05$. For the 1.2 Hz pendulum, $A_p$ was approximately constant and close to the desired target amplitude, but it showed a marked increase at the fastest target frequency of 1.3 Hz (see Table 1). The slower pendulum clearly undershot the target amplitude, for frequencies lower than 0.8 Hz and overshoot it for higher frequencies. The amplitude response ran counter to behavior found for a driven linear or nonlinear oscillator; for those oscillators, faster forcing frequencies lead to a smaller amplitude in the driven oscillator, whereas slower forcing frequencies produce larger amplitudes. The variability in $A_p$, as captured by standard deviations $SD(A_p)$, increased with target frequency, uninfluenced by pendulum $SD(A_p), F(6, 24, 31.20) = 2.87, p < .05$.

Positional Error RMSE

Because $T_p$ and $A_p$ gave only a first estimate of the timing and magnitudes of the peaks, we evaluated the accuracy of the continuous trajectories by calculating the RMSE. ANOVA results showed that with increasing target frequency, participants were less able to track the target accurately, as indicated by an increasing RMSE, $F(12, 60) = 49.04, p < .001$ (see Figure 6). Because the increase was monotonic across the 13 target frequencies, a linear regression was performed that achieved an $r^2$ of .74, $p < .001$. The regression equation was as follows: $RMSE = .06 \omega_T + .04$, with $\omega_T$ denoting the target frequency in hertz. That finding concurs with results found in numerous other studies in the tracking literature (Langenberg, Hefer, Kessler, & Cooke, 1998; Noble, Fitts, & Warren, 1955; Pew, Duffendack, & Fensch, 1967; Poulton, 1974). RMSE was insensitive to pendulum, indicating that actors were able to use either of the two pendulums to achieve the same degree of accuracy in tracking. In contrast, Pew et al. (1967) found that in a compensatory tracking task in which joysticks with different spring constants were used, the accuracy varied as a function of the stiffness and the target frequency. Particularly after practice, selected joystick stiffnesses produced more accurate tracking. The authors conjectured that participants may learn to exploit the natural resonance frequency of the manipulandum.

Taken together, the present cycle and error results indicate that participants were able to accurately perform the correct $T_p$ with either pendulum. $A_p$ was also close to the target amplitude, although the slower pendulum showed a significant change from under- to overshoot with increasing target frequencies. Variability in $T_p$ decreased, whereas $A_p$ variability increased with faster target frequencies. The continuous error measure RMSE increased monotonically with faster target frequencies, reflecting greater contribution of the amplitude than of the timing errors. However, the different pendulum properties had no differential effect.

Spectral Analysis

Although the kinematic measures used thus far captured the general accuracy of the tracking task, they did not provide any information as to the temporal nature of the deviations from the target. To that end, we further examined the kinematic behavior in the frequency domain. As noted in the beginning of this article, intermittency has been defined as the fluctuations in the response at frequencies other than the target frequency (Millard et al., 1993). A first set of spectral analyses was performed on the angular velocity data, and a second set was performed on the residual time series of angular velocity in which the main sinusoidal component had been removed (see Method section, Data Reduction and Dependent Measures). Fast Fourier transform (FFT) analysis on the angular velocity data revealed, as expected, a significant primary peak located at the target frequency. That finding was confirmed by a main effect for target frequency in the ANOVA, $F(2.28, 11.39) = 116.005.0, p < .001$. Peak frequency was not significantly affected by pendulum. The power at the primary peak in the spectrum rendered a significant effect for target frequency, $F(4.42, 22.12) = 28.01, p < .001$. That effect was mainly caused by
the significant reduction in peak power at the slowest target frequency of 0.1 Hz; at that frequency, the peak power was approximately half of the power of all other target frequencies. Post hoc Tukey least significant difference tests established that impression, with a significant difference between 0.01 Hz and all other target frequencies ($p < .001$). Note that that effect occurred despite the normalization of the velocity signal. An interaction of pendulum and target frequency was observed, $F(12, 60) = 2.52, p < .01$, with the faster pendulum having greater peak power from 0.1 to 0.7 Hz. Between 0.8 to 1.3 Hz, it was the slower pendulum that showed more power at the primary peak in the spectrum. Note that the relative change occurred at the eigenfrequency of the slower pendulum. That pattern of interaction repeated the one found for $A_P$ earlier. The only difference from the $A_P$ results was the marked difference found for the
TABLE 1
Means of Period and Amplitude Measures for Different Combinations of Pendulum and Target Frequency in Experiment 1

<table>
<thead>
<tr>
<th>Target frequency (Hz)</th>
<th>Mean period (s)</th>
<th>Standard deviation of period (s)</th>
<th>Mean amplitude (rad)</th>
<th>Standard deviation of amplitude (rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2-Hz-eigenfrequency pendulum</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>10.15</td>
<td>0.73</td>
<td>0.54</td>
<td>0.04</td>
</tr>
<tr>
<td>0.2</td>
<td>5.00</td>
<td>0.35</td>
<td>0.52</td>
<td>0.04</td>
</tr>
<tr>
<td>0.3</td>
<td>3.34</td>
<td>0.24</td>
<td>0.53</td>
<td>0.04</td>
</tr>
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<td>0.4</td>
<td>2.50</td>
<td>0.16</td>
<td>0.51</td>
<td>0.05</td>
</tr>
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<td>0.05</td>
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<tr>
<td>0.6</td>
<td>1.67</td>
<td>0.09</td>
<td>0.52</td>
<td>0.05</td>
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<td>0.7</td>
<td>1.43</td>
<td>0.07</td>
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<td>0.05</td>
</tr>
<tr>
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</tr>
<tr>
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<tr>
<td>1.2</td>
<td>0.83</td>
<td>0.04</td>
<td>0.53</td>
<td>0.06</td>
</tr>
<tr>
<td>1.3</td>
<td>0.77</td>
<td>0.04</td>
<td>0.56</td>
<td>0.06</td>
</tr>
</tbody>
</table>

| 0.8-Hz-eigenfrequency pendulum |
| 0.1                   | 10.10           | 0.98                            | 0.52                 | 0.05                                 |
| 0.2                   | 5.01            | 0.44                            | 0.51                 | 0.04                                 |
| 0.3                   | 3.35            | 0.23                            | 0.51                 | 0.04                                 |
| 0.4                   | 2.51            | 0.16                            | 0.51                 | 0.05                                 |
| 0.5                   | 2.00            | 0.12                            | 0.51                 | 0.05                                 |
| 0.6                   | 1.67            | 0.08                            | 0.52                 | 0.05                                 |
| 0.7                   | 1.43            | 0.07                            | 0.51                 | 0.05                                 |
| 0.8                   | 1.25            | 0.06                            | 0.53                 | 0.06                                 |
| 0.9                   | 1.11            | 0.04                            | 0.55                 | 0.06                                 |
| 1.0                   | 1.00            | 0.04                            | 0.54                 | 0.06                                 |
| 1.1                   | 0.91            | 0.04                            | 0.53                 | 0.06                                 |
| 1.2                   | 0.83            | 0.04                            | 0.55                 | 0.06                                 |
| 1.3                   | 0.77            | 0.04                            | 0.53                 | 0.06                                 |

The slowest target frequency. One reason for the considerably different result for the 0.1-Hz condition is that when target movement was captured in terms of period, the 0.1-Hz target frequency had a peak-to-peak period of 10 s, compared with the next slowest condition of 5 s (0.2 Hz). To assess the change in intermittency at the slower target frequencies, one must investigate target periods between 5 and 10 s. That issue was addressed in Experiment 2.

To further assess signs for intermittency, we analyzed the residual time series of angular velocity, with the main sinusoidal component removed. Our goal in the subtraction was to remove the dominating fundamental frequency to better reveal low amplitude cyclicities at frequencies other than the target frequency. The power spectra of individual trials and the superposed mean for a subset of eight target frequency and pendulum combinations are shown in Figure 4. The left column of panels represents the slower pendulum; the right column represents the faster pendulum. Note that the scale of the ordinate changed considerably across target frequencies. The most salient finding is that the power increased with faster target frequencies. That was true for power concentrated at the highest peak as well as for $P_{COG}$. A 2 × 13 ANOVA performed on $P_{COG}$ identified that increase as significant, $F(2.37, 11.86) = 56.40, p < .001$. In addition, the faster pendulum had significantly greater power than the slower pendulum, $F(1, 5) = 70.83, p < .001$. Furthermore, an interaction was found such that $P_{COG}$ was similar for both pendulums at the slower target frequencies, with the faster pendulum showing greater $P_{COG}$ than the slower pendulum at higher target frequencies, $F(4.71, 23.57) = 18.68, p < .001$.

The present results run counter to expectations based on the time series illustrated in Figure 3 and compared with previous findings that the degree of intermittency increases with slower target frequencies (Doeringer & Hogan, 1998; Miall et al., 1993). Inspection of the spectral results in Figure 4 exemplifies the finding that for the higher target frequencies, the peak power occurred at, or close to, the target frequency and, hence, cannot be attributed to increasing intermittency. That tendency was similarly seen for both
FIGURE 4. Power spectra of the residual time series for eight exemplary pendulum-target frequency conditions, showing all individual spectra together with the overall average, represented by the bold line. The left panel shows spectra of trials performed with the slower, 0.8-Hz pendulum, the right panel shows trials performed with the faster, 1.2-Hz pendulum. Each row shows trials with the same target frequency.
pendulums. From inspection of the residual time series, it is evident that the cyclicity at the main movement frequency was caused by varying overshoots and undershoots of the amplitude, especially at higher frequencies. That finding was already quantified in the amplitude analysis discussed previously. In conclusion, the periodicity in the time series again overshadowed the identification and interpretation of spectral results. We therefore return to FFT analyses once more later in the section on relative phase.

One final observation from Figure 4 is that, especially for the 1.2-Hz pendulum, additional peaks were observed at multiples of the target frequency. That feature is a signature of sinusoidally forced nonlinear oscillators (e.g., Andronov, Vitt, & Khaikin, 1966) and, hence, should not be interpreted as intermittent error corrections.

Relative Phase

In the literature on interlimb coordination from a dynamic systems perspective, it has been pointed out that the phase relations observed within and between actors are captured in the coupled oscillator model (Amazeen et al., 1998; Byblow et al., 1995; Kelso, 1995; Schmidt, Carello, & Turvey, 1990). To assess the hypothesis that tracking a rhythmic visual target can be understood as the coupling between two oscillators, we determined the relative phase $\psi$ between target and pendulum in phase space. The conditions led to 26 pairings, each of which was characterized by a value of detuning $\delta$, the difference between the eigenfrequency of the pendulum and the target frequency. Detuning $\delta$ ranged from -0.5 Hz to 1.1 Hz, with overlapping values for the two pendulums between -0.1 and 0.7 Hz. Two specific predictions have arisen from coupled oscillator models studied in the literature on interlimb and interperson coordination (Amazeen, Sternad, & Turvey, 1996; Collins, Sternad, & Turvey, 1996; Schmidt, 1993; Sternad, Amazeen, & Turvey, 1996; Sternad et al., 1992).

First, as the eigenfrequency of the pendulum becomes faster relative to the target’s frequency, the pendulum should lead the target by an approximately linearly increasing amount until $\psi$ reaches $\pi/2$. In contrast, as the target frequency becomes faster relative to the pendulum’s eigenfrequency, the performer will lag the target. Second, the stability of the wrist–pendulum and target system should decrease as the difference between the preferred pendulum and target frequency increases. The stability index, typically the standard deviations of relative phase, relates to a U-shaped function to the detuning $\delta$, where the minimum is centered at $\delta = 0$.

Before analyzing the means of $\psi$, we inspected the individual trials’ time series of $\psi$ to assess whether phase wrapping occurred. Phase wrapping did not occur in any of the trials, indicating that, on average, the targets were tracked at the prescribed frequency. When we conducted the same ANOVA as described previously, $\psi$ yielded a main effect for frequency, showing that $\psi$ changed with target frequency, $F(4,33, 21.64) = 4.48, p < .01$, and indicating that participants tended to lead the target more with increasing target frequency. Yet the values were relatively small, starting from a mean of $-0.05$ rad up to a maximum of $0.11$ rad at 1 Hz. A significant interaction between target frequency and pendulum was found, $F(8,39, 41.93) = 6.41, p < .001$.

From the perspective of coupled oscillators and the predictions just listed, the interaction effects can be better captured when $\psi$ is analyzed as a function of $\delta$. In the plot of $\psi$ against $\delta$, the expected monotonic relation between $\delta$ and $\psi$ was not found. Linear regressions calculated for each pendulum separately yielded two different negative slopes: 0.8-Hz pendulum, $\psi = 0.02 - 0.048, r^2(75) = .17, p = .13$; 1.2-Hz pendulum, $\psi = 0.11 - 0.178, r^2(76) = .63, p < .001$. Those results clearly conflict with predictions from coupled oscillator models that have been applied thus far to human interlimb movements.

Turning to the variability of relative phase, in the ANOVA on $D\psi$, a significant difference across target frequencies was found, $F(3,33, 19.67) = 7.75, p < .001$. A minimum in $D\psi$ was observed at 0.9 Hz, with an increase in the variability as target frequency increased or decreased. The slower pendulum was found to vary less in $\psi$ than the faster pendulum, $F(1,5) = 21.52, p < .01$, an effect that can be ascribed to the filtering properties in the heavier pendulum. No interaction was observed.

In Figure 5, the data in the space of $D\psi$ and $\delta$ are plotted. When both pendulums’ data were regressed separately, the relation between $\delta$ and $D\psi$ revealed two approximate U shapes within the range investigated. That relation was captured in terms of two highly significant quadratic regressions: 0.8-Hz pendulum, $D\psi = 0.21 + 0.24\delta^2, R^2(75) = .70, p < .001$; 1.2-Hz pendulum, $D\psi = 0.28 - 0.10\delta + 0.13\delta^2, R^2(75) = .42, p < .001$. Whereas the faster pendulum showed a relatively shallow curvature in which the minimum of the $D\psi$ values was not as clearly discernible, the $D\psi$ values of the slower pendulums showed a minimum at $\delta = 0$, in accordance with the coupled oscillator predictions. When variability in $\psi$ is considered as a reverse index for stability, that indicates that stability is maximal in the vicinity of $\delta = 0$ and decreases as $|\delta| > 0$. That result highlights the notion that the symmetry between the tracked and tracking oscillator captured in the detuning $\delta$ determines the shape of the variability.

Yet, the regressed functions for the two pendulums were separated, indicating that $\delta$, the asymmetry between the two oscillations, did not account for all of the variance in $D\psi$. The faster pendulum showed a flatter response across $\delta$, with significantly higher variability, whereas the slower pendulum’s variability was more dependent on $\delta$, having a clear minimum around $\delta = 0$. Although the U-shaped relation between $D\psi$ and $\delta$ suggests that coupled oscillator models capture certain aspects of behavior, the difference between the pendulums is not predicted in coupled oscillator models currently applied to human interlimb coordination. One reason for the failure to predict the difference could be that a detuning parameter other than the arithmetic difference between the two oscillators should be consid-
Variability in Phase Space

In the right-hand panels in Figure 3, the pendular trajectories in phase space are illustrated. Whereas the phase portraits of the two trials in Figure 3A and B, which were performed at intermediate and fast frequencies, show the typical smooth circular band of trajectories indicative of a stable limit cycle oscillation, it can be readily seen that for the slowest driving frequency in Figure 3C that feature is no longer present. It appears that at slower frequencies, the oscillator model in which a limit cycle attractor underly the behavior is assumed may be violated. In an effort to quantify those changes, we calculated a measure of harmonicity, \( H \) (see, in Method section, Data Reduction and Dependent Measures). In the ANOVA, we detected an increase in \( H \) with decreasing target frequency, \( F(4.94, 24.72) = 120.18, p < .001 \), and that the faster pendulum showed a greater difference from a pure harmonic oscillation than the slower pendulum, \( F(1, 5) = 92.77, p < .001 \). To test to what degree that measure is a function of the symmetry properties, we plotted \( H \) against \( \delta \). As shown in Figure 6, for each of the two pendulums, \( H \) increased with larger values of \( \delta \) (shown by the hollow symbols). The minimum was close to \( \delta = 0 \). Most interesting, the slope of the results was opposite to the one seen in the positional error measure RMSE. To highlight the opposing trends, we plotted both measures together as a function of the asymmetry.

Earlier, we attempted to extract temporal features of the trajectory's variability by performing FFT analyses on velocity signals. The results and their interpretation suffered from the shortcoming that variable amplitude over- and undershoots obscured lower amplitude spectral components that could be attributed to intermittency. In relative phase, those amplitude variations were no longer as prominent and no longer confounded the spectral analysis. The same FFT analyses were performed on the time series of continuous relative phase, and the following results are illustrated by two representative conditions in Figure 7. As before, all trials' data in the particular condition were superposed together with the mean. In the left panel, which shows a condition with \( \delta = 0 \), there is a peak at approximately 0.5 Hz, which is not at the target frequency 0.8 Hz. Comparing that spectrum with the one in the right panel (\( \delta = 0.4 \) Hz), it is evident that there was more overall power and that that power was concentrated in several peaks at superharmonic frequencies. To verify those impressions quantitatively, we calculated \( P_{COG} \) and \( f_{COG} \) for all conditions. The ANOVA on \( P_{COG} \) underscored the visual impression that the faster pendulums contained more power, \( F(1, 5) = 25.45, p < .01 \). In addition, in support of the qualitative picture in Figure 3, higher target frequencies were associated with less power, \( F(3.49, 17.44) = 33.68, p < .001 \). The results on \( f_{COG} \) showed a similar pattern. Faster pendulums
showed power at greater frequencies, $F(1, 5) = 190.60, p < .001$. The location of that power decreased with increasing target frequency, $F(5.52, 27.61) = 93.08, p < .001$, in accordance with results in the literature (Doeringer & Hogan, 1998; Miall et al., 1993). An interaction was also reported, $F(2.74, 13.71) = 11.50, p < .001$, indicating again that both pendulums, in conjunction with target frequency, had an influence on the fluctuations.

Subsequently, and similarly to the other relative phase measures, we plotted and regressed $P_{\text{COG}}$ and $f_{\text{COG}}$ against $\delta$ (Figure 8A and B) to scout for their dependency on the task asymmetry. Second-order polynomial regressions against $\delta$ showed significant results, as illustrated in Figure 8. The regression equations for the two pendulums are: 0.8-Hz pendulum, $P_{\text{COG}} = .01 + .05\delta + .19\delta^2$, $R^2 (75) = .88$; 1.2-Hz pendulum, $P_{\text{COG}} = .07 - .20\delta + .39\delta^2$, $R^2 (75) = .88$; 0.8-Hz pendulum, $f_{\text{COG}} = .56 - .55\delta + 1.07\delta^2$, $R^2 (75) = .81$; 1.2-Hz pendulum, $f_{\text{COG}} = .95 - .09\delta + 1.69\delta^2$, $R^2 (75) = .80$. The coefficients for the second-order terms were all significant, and $R^2$s improved over linear regressions. In support of the
patterning found for $H$, those spectral estimates again were shown to be a curved function of $\delta$, where the minimum was reached close to $\delta = 0$. Once again, the asymmetry between target and pendulum appeared to be a strong order- ing factor for the intermittency, as quantified both in $P_{\text{COG}}$ and $f_{\text{COG}}$ and in $H$.

To summarize the major results, the investigation of the intermittency issue revealed that the fluctuations in the endpoint trajectory varied with the inertial properties of the effector. Moreover, the spectral analyses revealed indications that it is the relationship between the characteristics of the visual target motion and the effector that shapes the fluctuations seen in the endpoint trajectory. The analysis of phase relations between the tracked and the tracking oscillation revealed a constant relative phase close to zero across different frequency relations, signaling that the model of bidirectionally coupled oscillators, as for instance is suggested in the HKB model (Haken et al., 1985), is inadequate for this tracking task. Yet, fluctuations in relative phase were consistent with the predicted U-shaped dependency on detuning, indicating that it is the symmetry between the target and effector that determines the degree of fluctuations. Similarly, deviations of the pendulum's trajectory from a harmonic wave showed a systematic dependency on $\delta$.

**EXPERIMENT 2**

In Experiment 1, we investigated sinusoidal visuomotor tracking of 13 target frequencies between 0.1 Hz and 1.3 Hz that were separated by 0.1 Hz. Two wrist–pendulums with different inertias and eigenfrequencies were used for all target conditions. Analyses of intermittency revealed that, although there were systematic gradual changes in the dependent measures as a function of target frequency, the results for the 0.1-Hz (10 s) target condition often differed markedly from those of the 0.2-Hz (5 s) and the higher fre-}

quency conditions. That finding is not surprising, because, when the conditions were converted to periods, there was a disproportionately wide gap between the lower frequency conditions. The phase portrait analysis suggested that the limit cycle attractor characteristics changed markedly for the very slow targets. The most marked differences in the regression analyses of relative phase and power spectral measures were found at ranges of $\delta$ greater than 0.6, that is, conditions where slow target frequencies were present. To investigate whether the change in the lower frequency conditions is, in fact gradual, as was seen for the higher range of frequencies, or whether there is a critical frequency or frequency relation at which tracking behavior changes qualitatively, we conducted a second experiment that "filled this gap" in the conditions. Eight target periods between 0.1 Hz (10 s) and 0.33 Hz (3 s) were tested, and the two pendulums' eigenfrequencies were kept identical.

**Method**

**Participants**

The volunteers who had participated in Experiment 1 again participated in Experiment 2.

**Apparatus and Materials**

The same apparatus as in Experiment 1 was used. To provide comparability with the previous data set, we used the same two pendulums (eigenfrequencies at 0.8 Hz and 1.2 Hz).

**Procedure and Design**

Eight target periods were selected, 10, 9, 8, 7, 6, 5, 4, and 3 s, corresponding to the following frequencies: 0.10, 0.11, 0.13, 0.14, 0.16, 0.20, 0.25, and 0.33 Hz. Participants performed 4 practice trials at target frequencies of 0.10, 0.13,
TABLE 2
Means of Period and Amplitude Measures for Different Combinations of Pendulum and Target Frequency in Experiment 2

<table>
<thead>
<tr>
<th>Target frequency (Hz)</th>
<th>Mean period (s)</th>
<th>Standard deviation of period (s)</th>
<th>Mean amplitude (rad)</th>
<th>Standard deviation of amplitude (rad)</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>1.2-Hz-eigenfrequency pendulum</td>
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</tr>
<tr>
<td>0.10</td>
<td>10.32</td>
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<td>0.03</td>
</tr>
<tr>
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<td>0.53</td>
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</tr>
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<td>0.53</td>
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<td>0.03</td>
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<td>0.53</td>
<td>0.05</td>
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<td>0.8-Hz-eigenfrequency pendulum</td>
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<tr>
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<td>3.04</td>
<td>0.15</td>
<td>0.54</td>
<td>0.03</td>
</tr>
</tbody>
</table>

0.20, and 0.33 Hz before being tested. During those practice trials, half of the participants used the 1.2-Hz pendulum, whereas the other half swung the 0.8-Hz pendulum. Continuing with the same pendulum, the participants then performed 2 trials at each of the eight target frequencies, in random order. After completion of 4 practice trials and 16 test trials, the participants switched to the other pendulum and repeated the same procedure. The total number of trials, including practice, was 40. All trials were performed in a single session. Participants were given at least 1 min of rest after completing the first 20 trials.

Data Reduction and Dependent Measures

The same dependent measures were calculated as in Experiment 1. We separately analyzed each dependent variable by using a two-way repeated measures ANOVA with two levels of pendulum and eight levels of target frequency. In cases of violations to the assumption of sphericity, we adjusted the degrees of freedom by computing the epsilon correction factor according to the Huynh–Feldt method (Girden, 1992).

Results and Discussion

Cycle Analysis

As expected, the peak-to-peak period $T_p$ of the actor's pendular motions varied with target frequency, $F(3.07, 15.34) = 4.421.70, p < .001$. Pendulum did not significantly influence $T_p$, as indicated by the absence of both a main effect of pendulum and an interaction of pendulum and target frequency. In agreement with Experiment 1, no drift in period was observed. Variability of $T_p$, as shown in the standard deviations $SD(T_p)$, increased with slower target frequencies, $F(2.41, 12.06) = 12.21, p < .005$. The variability in $T_p$ was not influenced by pendulum; nor did it show an interaction of pendulum and frequency. Taking both experiments together, that finding shows that $T_p$ closely matched target oscillation periods between 0.75 s and approximately 8.0 s, but a further slowing down of the oscillation reduced performance such that there was a tendency to undershoot the period and have greater variability. From an oscillator interpretation, the observed detriment in performance can be attributed to the fact that an effector system with a considerably faster intrinsic frequency loses its limit cycle stability at such slow frequencies and can no longer track smoothly.

The mean amplitude $A_p$ was significantly affected by pendulum, $F(1, 5) = 8.79, p < .05$, such that participants tended to produce $A_p$s larger than the target amplitude with the faster pendulum and smaller than the target with the slower pendulum. The change across frequencies was gradual, not differentiating the very slow target conditions from the fast ones. The effect of frequency approached significance, $F(4.99, 24.96) = 2.48, p = .06$, showing a increasing undershoot in $A_p$ at slower target frequencies. Although only a trend, that effect is in line with Experiment 1, where
for lower frequencies undershoots were found. The variability in $A_P$ was not significantly influenced by either pendulum or target frequency. Amplitude and period analyses are summarized in Table 2.

In the analysis of the continuous error $RMSE$, the same effects as in Experiment 1 were found. With increasing target frequency, participants were less able to track the target accurately, as indicated by a monotonically increasing $RMSE$, $F(1.80, 8.97) = 11.52, p < .005$. The slower pendulum led to a significantly greater error, $F(1, 5) = 7.57, p < .05$. Note that the slower frequencies did not change the $RMSE$ error in a discontinuous fashion. A comparison with the data of Experiment 1 showed that across the same range of frequencies a difference between pendulums was also observed; the difference was not statistically significant, however. It should also be pointed out that the absolute values of $RMSE$ were lower than in Experiment 1. The same set of individuals participated in both Experiments; therefore that finding points to a practice effect (Pew et al., 1967).

**Relative Phase Analysis**

Turning to relative phase $\psi$ between the pendulum and target movements, we first inspected the raw time series of $\psi$ to identify trials with phase wrapping. In none of the trials did participants deviate in their tracking frequency, and relative phase always fluctuated around a mean value. An ANOVA did not reveal any significant effects for pendulum and frequency, in accord with Experiment 1 (Heftter & Langenberg, 1998). In an analysis of $\psi$ with respect to the asymmetry between the target and eigenfrequency, $\delta$, no significant relation was discerned. The values were very unsystematic and on average close to zero. The estimate for stability, $\Delta\psi$, increased significantly for slower target frequencies, $F(2.22, 26.08) = 16.77, p < .001$. No other effect was obtained. The relation between $\Delta\psi$ and $\delta$ was captured by first- and second-order polynomial regressions. When performed separately for the two pendulums, both pendulums showed a significant linear relation: 1.2-Hz pendulum, $\Delta\psi = -0.20 + 0.45\delta$, $r^2(46) = .52, p < .001$; 0.8-Hz pendulum, $\Delta\psi = 0.06 + 0.32\delta$, $r^2(46) = .60, p < .001$. The results of each pendulum separately showed a decrease in $\Delta\psi$ with smaller values of $\delta$, in line with the expectations from the coupled oscillator model. A U-shaped relation was not found here because, in the conditions tested, only $\delta > 0$, ranging between 47 Hz and 1.1 Hz, were used; hence, only part of the curve was tested. The data here again showed that the relation between $\Delta\psi$ and $\delta$ is best captured separately for each pendulum, indicating that the difference between the pendulum eigenfrequency and the target frequency alone is not a sufficient detuning parameter to capture the results.

**Variability in Phase Space**

Last, the variability of the trajectory in phase space was evaluated. Harmonicity $H$ decreased as target frequency increased, $F(3.89, 19.46) = 42.51, p < .001$, and the faster pendulum had significantly higher values, $F(1, 5) = 7.44, p < .05$. Both results were in accord with Experiment 1, indicating that with slower target frequency and faster pendulums the phase portrait displayed a greater variability and discrepancy from sinusoidal behavior. When the error measure $RMSE$ and $H$ were viewed together, the same opposing trends as in Experiment 1 were discerned (see Figure 6).

**Spectral Analyses**

For an evaluation of the frequency characteristics of the trajectories' fluctuations, in the analyses of Experiment 1 we identified that FFT analyses on relative phase were most sensitive for lower amplitude cyclicities outside the target frequency. Therefore, spectral analyses were again performed on continuous relative phase, and the center-of-gravity measures, $P_{COG}$ and $f_{COG}$ were determined. As above, we regressed the overall averages against $\delta$ by using a polynomial function in order to test for the U shape predicted by the coupled oscillator model. Figure 8 includes the results of that experiment. The polynomial fits were significant overall, and in particular for the second-order coefficient. The regression equations were: 0.8-Hz pendulum, $P_{COG} = .72 - 2.56\delta + 2.45\delta^2$, $R^2(45) = .57$; 1.2-Hz pendulum, $P_{COG} = 5.29 - 11.34\delta + 6.18\delta^2$, $R^2(45) = .40$; 0.8-Hz pendulum, $f_{COG} = 4.47 - 12.70\delta + 11.91\delta^2$, $R^2(45) = .36$. The 1.2-Hz pendulum did not produce a significant quadratic fit for $f_{COG}$.

**GENERAL DISCUSSION**

In the present study, the experimental task of visuomotor tracking of sinusoidal targets was investigated. That task is at the interface of two lines of research that have been driven by two conceptual frameworks associated with different sets of analyses: First, visuomotor tracking is an experimental paradigm that has been central to research pursuing the hypothesis that humans act as intermittent servo-controlers. In numerous studies, researchers have probed the question of whether the observed "nonsmoothness" in the movement trajectory is the signature of intermittent control. It is assumed that the human operator generates movements by using a fundamentally discrete strategy, even in a predictable rhythmic task. An expectation of that hypothesis is that directional changes in the tracking trajectory will occur at a limited band of frequencies, depending on the system's transfer function; specifically, on the delay. Second, the task of manual tracking of an oscillatory target is a variation of the rhythmic interlimb coordination paradigm that has dominated in the research pursuing a dynamic systems interpretation of visuomotor coordination. In that tradition of research, rhythmic tracking movements should be best understood as entrainment between the oscillations of the target and the actor. If coupling is continuous, then the fluctuations in the tracking trajectory should be interpreted as an expression of the stability of a dynamic system. A consequence of that hypothesis is that those fluctuations should
be a function of the incompatibility, or asymmetry, between the task and the effector.

We designed two experiments to investigate those issues. Using the wrist–pendulum paradigm, participants swung a hand-held pendulum with their dominant hand in the sagittal plane, tracking a vertically moving target that oscillated at different frequencies with a constant amplitude. We used two different pendulums with different inertias and eigenfrequencies to test the influence of mechanical properties of the effector system. In a first line of analyses, we tested dependent measures traditionally derived in tracking studies, particularly kinematic error measures and spectral analysis. In the second set of analyses, we used dependent measures typically applied in studies on rhythmic coordination from a dynamic systems' perspective, particularly examining relative phase and its variability. Whereas the cycle measures were focused mainly on the input–output relation, comparing the target (input) with the tracking trajectory (output), in the second set of analyses we examined human performance in terms of the relative properties between the target and pursuit oscillation. Specifically, relative phase and its variability and the harmony of the trajectory were analyzed as a function of the symmetry between task and effector (see Figure 1).

**Intermittency as a Function of Target Frequency and the Manipulandum’s Inertia**

Support for intermittent control processes in pursuit tracking of both predictable and unpredictable targets has come from the finding of discontinuities in the velocity signal, as detected by the number and frequency of directional changes or by spectral analyses. Power concentrated at limited frequency bands at frequencies other than the dominant frequency has been interpreted as the main evidence for intermittent control. Our analyses, which followed the studies on intermittency, produced a set of results in accordance with the literature: The most robust result was that positional error RMSE increased with increasing frequency or velocity of the target. The positional error was mainly composed of a discrepancy in the amplitudes and phase, because response period generally matched the target period. The amplitudes themselves showed an interaction between target frequency and pendulum, pointing to the fact that effector properties play an important role. The slower pendulum undershot the target for lower frequencies, whereas it overshot it for higher frequencies.

Spectral analyses of the tracking velocity, the residual time series, and relative phase further emphasized the combined influence of the visual target and the effector that shapes the frequency content of the fluctuations seen in the endpoint trajectory. Analysis of the primary peak in the spectrum showed a disproportionately large decrease in power for the slow target frequency. Although, because of the effects from the predominant frequency, those results do not illuminate the issue of intermittency, the spectral analysis of the residual trajectory was also clouded by amplitude errors, especially at faster target frequencies. That left systematic periodicities, which cannot be considered as intermittency. As a next step, spectral analyses were performed on relative phase, where such periodicities were no longer dominant. The spectral results yielded an increase in power with decreasing target frequency or velocity, capturing the pattern of results observed in the phase portraits of Figure 3 and supporting the previous literature on intermittency in visuomotor tracking (Doeringer & Hogan, 1998; Miall et al., 1993). In addition, the inertia of the pendulum led to a reduction in the degree of intermittency observed. Note that, although many researchers have investigated the influence of mechanical characteristics of the manipulandum (e.g., Bahrick, Bennett, & Fitts, 1955; Howland & Noble, 1955; Notterman & Page, 1962), we did not find studies in which the dynamical compatibility between target and task has been systematically pursued.

Of special interest is the finding that the spectral measures of relative phase systematically varied with the relationship between the target frequency and the pendular eigenfrequency, as captured in the detuning term $\delta$. Notably, it was not only the power but also the location of that concentrated power that changed systematically with $\delta$. The observation that intermittent changes do not occur at fixed time intervals, but rather depend on task and manipulandum properties, has important implications for the interpretation of intermittency. Our results, therefore, do not support the interpretation that the frequency of fluctuations in the movement trajectory is a direct reflection of delays in the perceptuomotor loop (e.g., Craik, 1947; Neilsen, Neilsen, & O'Dwyer, 1988; O'Dwyer & Neilsen, 1998). Therefore, the search for the one transfer function that captures the input–output relations has proven to be a nontrivial problem, even in a rhythmic predictable task. That pursuit has previously been criticized as leading to an impasse (Hammerton, 1981). In addition, the observation that peaks occurred at superharmonic frequencies can be captured in a continuous coupled oscillator model and, hence, are not necessarily indicative of error corrections.

**Entrainment Between Coupled Oscillations: Fluctuations in Relative Phase Depend on the Symmetry Between Oscillations**

Motivated by the literature on entrainment between oscillations, in which that phenomenon has been demonstrated in a wide range of systems, ranging from the flashing of fireflies to sleep entrained to the circadian cycle (Strogatz, 1987; Strogatz & Stewart, 1993), we believe it is feasible to hypothesize that tracking a predictable rhythmic target is similarly governed by an entrainment process. The human rhythmic movement, assumed to be a stable oscillation, would be coupled to the visually presented target. Instead of a discrete and explicit compensation of visually perceived errors, it is the coupling between target and movement that determines frequency, amplitude, and phase between the two rhythmic components. The actor's strategy would be to
parameterize his or her oscillation and the coupling—once for the entire trial. The attractive feature of that strategy is that during such stable performance, perturbations—or errors—relax back to the limit cycle and need not be actively corrected (see also Sternad, Duarte, Katsumata, & Schaal, 2000, in press). Note, though, that a servo-controller can also be regarded as a dynamic system. Even the classical PD controller follows equations formally equivalent to a mass spring system, producing a restorative force proportional to the deviation from equilibrium or desired trajectory. Yet, in the notion of an attractor regime it is assumed that the return to equilibrium is brought about by properties of the physical system or “plant” itself, whereas in the control hypothesis it is implied that the division between a control level and a plant is such that errors in performance are explicitly detected and corrected by the controller. Still, the two models can often be transformed into each other (see Pressing, 1998).

In the context of the coupled oscillator hypothesis, smoothness of performance is a function of the dynamic stability of the task–effector system. One control parameter determining the stability of the task–effector system is the symmetry between the two oscillations, or similarity in their intrinsic dynamics. Lower stability is associated with a higher degree of fluctuations because of the likely presence of stochastic perturbations. To assess that hypothesis, one evaluates the phase relations between the tracked and the tracking oscillation as a function of the symmetry between the two oscillatory frequencies. The symmetry is captured in the detuning term $\delta$, defined as the arithmetic difference between the target frequency and the eigenfrequency of the wrist–pendulum system. Explicit predictions are tested as derived from the most frequently investigated model of coupled oscillations, the HKB-model (Haken et al., 1985).

The results have not provided unequivocal support. A phase relation close to zero with no dependency between $\delta$ and $\psi$ runs counter to the prediction that relative phase has a systematic dependency on detuning. The present findings concurred with results of Liao and Jagaciński (2000), who also reported zero relative phase in sinusoidal pursuit tracking. Further investigations into other detuning terms have not provided systematic results (Collins et al., 1996; Fuchs et al., 1996; Sternad et al., 1995). The negative finding signals that the model of bidirectionally coupled oscillators is inappropriate for visuomotor pursuit tracking. That result needs to be understood in light of the differences between the tracking situation and the model of coupled oscillations. Whereas in the HKB model it is assumed that two autonomous oscillators are coupled bidirectionally, the major difference between interlimb coordination and visuo-manual tracking is that the target oscillation is independent of the pendulum motions and only the actor adapts his or her movements. The coupling is unidirectional. In addition, accurate error information is continuously provided by the online visual display of both the pendulum and target positions on the monitor. That information probably aids the actor to overcome errors or phase differences in the performance and thereby overrides the entrainment strategy. That result highlights the clear contradiction to the interlimb situation.

Counter to the first rejection of the hypothesis of mutually coupled oscillators, analysis of the variability of relative phase provided support for an entrainment strategy. Fluctuations of tracking performance, quantified in terms of the uniformity of relative phase, were consistent with the expected U-shaped dependency on $\delta$, conforming with the predictions (see insert in Figure 5). Especially for the slower pendulum, there was a clear minimum for symmetric oscillations ($\delta = 0$). Even for the smaller range of $\delta$ in Experiment 2, the fluctuations significantly increased with $\delta > 0$. That result indicates that it is the matching between target and effector that determines the degree of fluctuations.

Although it is clear that the bidirectionally coupled model is inadequate, in three previous studies, models with unidirectional coupling between a reference and a phase-entrained oscillator have been proposed. The hypothesis that a trajectory coupled to a perceptual variable can be captured as a driven linear mass spring system has been suggested in work by Schöner (1991) and has been experimentally addressed by Dijkstra, Schöner, and Gielen (1994) in a postural task with an oscillating visual surround. The authors found the expected phase relations between the postural system and the visual surround, providing support for the oscillator model. Yet, they did not observe the predicted amplitude response for different visual oscillatory frequencies. The authors interpreted the absence of that effect by postulating that the actors are able to adapt the oscillatory properties of the postural system. Liao and Jagaciński (2000) analyzed sinusoidal tracking of pursuit and compensatory displays, both as position and velocity control. Those four task conditions translate into in-phase and antiphase, with 0 or 90° phase differences, respectively. The authors found support for the corresponding predictions from a coupled oscillator model, where stability of performance, measured as means and standard deviations of relative phase and amplitude ratio, is greatest for in-phase coupling, followed by antiphase and 90°. They suggested an adaptive forced oscillator model to capture the coupling between the performer, the visual display, and the system dynamics. Tass and colleagues (Tass, Wunderlin, & Schanz, 1995) developed a model for visuomotor tracking in which a synergic approach was adopted. Their focus in that work was specifically on modeling the time delays of the nervous system and delay-induced changes in the visual feedback displayed in the task, and in the experiments they focused on the manipulation of the visual delay quantified in proportion to the target frequency. Relative phase and dependent measures formulated by use of symbolic dynamics showed evidence for different dynamic regimes as a function of the visual delay. Phase
transitions from a fixed-point regime to oscillations and chaos were observed, in accordance with their model (Tass, Kurths, Rosenblum, Guasti, & Hefter, 1996). Although their modeling and experimentation was geared to a different aspect of the task, the work showed that stability in a dynamic system of coupled oscillators is a feasible framework for visuomotor tracking.

Changes in the Dominant Behavioral Regime as a Function of Task–Effector Symmetry

Viewing all analyses together, support and discordance were shown for both the intermittent servo-controller and the coupled oscillator hypotheses. The spectral results showed power concentrated at frequencies other than the target frequency; that is, there were signs of intermittency. However, we criticize the notion that the intermittency in the movement trajectory is necessarily indicative of intermittent control. When the nonsmoothness was measured as variability of continuous relative phase, the data conformed to stability predictions from the coupled oscillator model, showing systematic dependence on the asymmetry between target and manipulandum. Yet, there was also a problem in directly adopting a coupled oscillator model as the more appropriate interpretation: The very slow pendulum movements could no longer be regarded as the limit cycle behavior of an oscillator, and the results of mean relative phase did not match the predictions of the HKB model (Haken et al., 1985). Does that mean that neither of the two hypotheses is appropriate for understanding visuomotor tracking, or are both partially valid? As we described earlier, the distinction between the two traditions of modeling is less sharp than has traditionally been presented in the motor control literature. A controller is a dynamical system, and the control function can be nonlinear, creating attractor structures. Both dynamic systems and control systems can be discrete or intermittent or continuous, can include a referent, or can be mutually referential (Pressing, 1998, 1999). Indeed, results suggest that both interpretations can be reconciled when one views the behavioral regime as a function of the task–effector symmetry.

That argument can be developed around Figures 5, 6, and 8, viewing key variables in their interplay as a function of the detuning δ. Figure 6 reveals opposing trends for RMSE and H, demonstrating that the relative proportion of error and variability changed across different δ values. The change in the relative contribution was seen for both the 1.2- and the 0.8-Hz pendulums separately. In both cases, RMSE decreased as δ increased, with the high-inertia pendulum showing less fluctuations for the same δ values. Note, that that filtering effect became evident only when the RMSE values were plotted against δ. Whereas RMSE continued to show a monotonic course, the variability estimated in both H and Δy showed a curved relation, with the minimum of the curve close to δ = 0 (see Figure 5). Looking at conditions with δ > 0, where the pendulum tracked a relatively slower target, decreasing error was accompanied by greater fluctuations in both the individual pendulum’s limit cycle, H, and the relative coordination between target and the effector, shown in Δy (Figure 5), as well as in the spectral results of relative phase captured in Pcoo and Pcco (Figure 8). Participants were more accurate at relatively slower target frequencies but at the expense of greater fluctuations in performance. They made frequent adjustments in the response to maintain accuracy at the expense of a stable oscillatory behavior. The limit cycle for the slowest frequencies was no longer a smooth closed band but deviated markedly from the typical limit cycle seen in rhythmic movements performed at preferred speeds (Figure 3). Therefore, one can plausibly interpret that behavior as governed by feedback-based intermittent movements rather than as continuous entrainment. For δ < 0, where the effector tracked relatively higher target frequencies, the errors in performance increased, accompanied by greater fluctuations in the relative coordination, but with no change in the variability of the individual limit cycle. Accuracy was lost at the expense of smoother pursuit. That set of features appears to conform better to an oscillatory regime, such that the cycle parameters of amplitude, period, and coupling are set for the entire trial.

In conclusion, two approaches to perceptually guided action were examined, following their analyses and explanatory concepts. Both hypotheses received partial support. When the results were viewed with respect to the asymmetry of effector and task, a reconciliation of the two seemingly opposing approaches appeared: For movements where the target is relatively slower than the target frequency of the tracking effector, visually guided discrete correction processes appear to play a significant role, most closely corresponding to the concept of intermittency. When target frequency is higher than effector eigenfrequency, behavior appears to be dominated by an entrainment between target and effector. Those results become apparent only when dependent measures are viewed as a function of the dynamical compatibility or symmetry between target and effector.

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NOTE

1. In response to one reviewer, who raised the issue that the masses attached to the two pendulums varied with their eigenfrequencies and that mass in itself may be an important predictor for the preferred frequency, we conducted additional experiments. Four pendulums were assembled that had the same computed eigenfrequency of 5.02 rad/s (or 0.8 Hz) but differed in their masses and lengths. The following pendulum configurations were used: 48 cm with 250 g (as was used in the experiment), 62 cm with 20 g (which kept the mass identical to the second pendulum used in the experiment), 52 cm with 100 g, and 46 cm with 500 g.
Two participants were instructed to swing, in turn, one of those pendulums with their dominant hand at their preferred frequency for a duration of 40 s. Two trials were collected per pendulum. Mean periods and standard deviations were calculated and regressed against length, mass, and eigenfrequency. Mean periods and standard deviation across trials and the four pendulums were 1.239 ms ± 23 ms and 1.070 ms ± 26 ms for the 2 participants, respectively. Regression of the preferred period against attached mass yielded slopes close to zero, demonstrating that mass had no effect on the preferred frequency displayed by the participant. Therefore, it can be inferred that the approximation of the wrist-pendulum system as a simple undamped unforced pendulum is sufficient for the present questions and that the calculated eigenfrequency can serve as an appropriate basis for the analyses.

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