

# Visual Tracking and Entrainment to an Environmental Rhythm

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This study investigated the role that visual tracking plays in coupling rhythmic limb movements to an environmental rhythm. Two experiments were conducted in which participants swung a hand-held pendulum while tracking an oscillating stimulus or while keeping their eyes fixed on a stationary location directly above an oscillating stimulus. It was expected that the participants' rhythmic movements would become entrained to the oscillating stimulus in both conditions but that visual tracking would strengthen this entrainment. Experiment 1 investigated the role of visual tracking in establishing unintentional entrainment. Experiment 2 investigated the role of visual tracking in intentional entrainment. As predicted, participants exhibited greater unintentional coordination and more stable intentional coordination when they tracked the stimulus. These findings highlight the importance of understanding the role of eye movements in environmental coordination.

*Keywords:* eye movements, rhythmic movements, oscillator dynamic

Our daily behavior is coordinated with environmental rhythms at many time scales. Whether it is the relationship of our sleep-wake behavior with the environment's dark-light cycles, the timing of our footsteps to board an escalator, or dancing to music, we naturally synchronize our behavior with periodic environmental events. Much research has investigated the basis for these rhythmic environmental couplings using experimental paradigms in which rhythmic limb movements "track" an auditory (e.g., Repp & Penel, 2004) or visual stimulus (e.g., Buekers, Bogaerts, Swinnen, & Helsen, 2000). However, in these experimental paradigms, the role that the observable motor activity of the perceptual system itself plays in modulating the production of rhythmic coordination has not been investigated. For example, in visual tracking experiments, the eyes have been assumed to be a passive conduit for coupling limb rhythms to periodic environmental events. However, the eyes do move rhythmically during visual tracking tasks, and the effect that these rhythmic movements have on the ensuing coordinated

state has received very little attention. This article investigates this phenomenon—namely, the role that eye movements play when people become synchronized with a rhythmic visual event. Before we discuss the evidence that suggests that visual tracking and the movements of the eyes influence the stability of sensorimotor coordination, we review past research that has modeled coordination with a rhythmic environmental stimulus.

## Intentional Entrainment With an Environmental Rhythm

A number of studies have investigated whether one's ability to intentionally synchronize limb movements to rhythmic environmental sources is governed by dynamical processes of entrainment (Amazeen, Schmidt, & Turvey, 1995; Byblow, Chua, & Goodman, 1995; Kelso, Decolle, & Schöner, 1990; Liao & Jagacinski, 2000; Russell, de Rugy, & Sternad, 2004; Russell & Sternad, 2001; Schmidt, Bienvenu, Fitzpatrick & Amazeen, 1998; Schmidt, Carello, & Turvey, 1990; Schmidt & Turvey, 1994; Wilson, Collins, & Bingham, 2005; Wimmers, Beek, & van Wieringen, 1992). Inspired by rhythmic interlimb coordination investigations and dynamical systems theory (Kelso, 1995; Kugler, & Turvey, 1987), these studies have found that coordination of the actor's movements and the environmental rhythm can be modeled as two oscillatory regimes that are dynamically coupled via perceptual information. Generally, such studies use the relative phase angle created between the two oscillations as the collective variable that characterizes the coordinated state of entrainment, determine how different variables (e.g., phase mode, frequency of oscillation) affect its stability and change, and then evaluate whether these observations can be understood in terms of a formal model of dynamical entrainment. Some of these studies that have used a frequency-scaling paradigm (Byblow et al., 1995; Kelso, 1984; Kelso et al., 1990; Schmidt et al., 1990, 1998; Wimmers et al.,

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This research was supported by a National Science Foundation Grant BCS-0240266 awarded to R. C. Schmidt and National Science Foundation Grant BSC-0240277 awarded to C. A. Fowler, K. L. Marsh, and M. J. Richardson. We thank Takashi Mitsuya for help with data collection.

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1992) have demonstrated that antiphase coordination of a limb with an oscillating stimulus exhibits a breakdown at higher frequencies of oscillation, whereas inphase coordination does not. A similar antiphase breakdown is exhibited in interlimb coordination in the coordination of two wrists or index fingers (e.g., Kelso, 1984). These studies have found that a low-dimensional coupled oscillator equation (Haken, Kelso, & Bunz, 1985) can model the breakdown of antiphase coordination, and they have found that the predictions of this dynamical model hold true across different kinds of environmental couplings and conditions of perceptual information (e.g., Byblow et al., 1995; Kelso et al., 1990; Schmidt et al., 1990, 1998; Wimmers et al., 1992).

Other evidence for a dynamical organization of coordination with an environmental rhythm has been found using a steady state as opposed to a frequency-scaling coordination paradigm (Schmidt & Turvey, 1995). Such studies (Amazeen et al., 1995; Buekers et al., 2000; Liao & Jagacinski, 2000; Russell et al., 2004; Russell & Sternad, 2001; Schmidt & Turvey, 1994) again generally evaluate the patterning of relative phase between the limb movements and the oscillating stimulus. In line with the predictions of a coupled oscillatory dynamic (Haken et al., 1985), these studies have found greater relative phase lag and phase variability for (a) antiphase compared with inphase tracking, (b) higher tracking frequencies, and (c) greater system detuning (i.e., the difference between the inherent frequency of the limb and the frequency of the stimulus). The modeling efforts of the more recent studies have taken into account the fact that limb–environment couplings are different from interlimb coordination in their unilateral nature. The Haken et al. (1985) model of interlimb relative phasing is based on a bidirectional interaction between oscillators as observed in interlimb coordination. Because the Haken et al. model is technically only appropriate in those instances in which the environmental rhythm is another limb, recent studies (Liao & Jagacinski, 2000; Russell et al., 2004) have successfully modeled the unilateral limb–environment patterning of relative phase using an adaptive, forced oscillator system in which the visual information of the rhythmic stimulus is idealized as a rhythmic injection of energy into an oscillatory system and the parameterization of the oscillatory regime's components is adjusted by the participant to adapt to the conditions of the oscillating environmental stimulus. Similar dynamical models have been used to understand the entrainment of postural sway with environmental rhythms (Giese, Dijkstra, Schöner, & Gielen, 1996; see below).

### Unintentional Entrainment With an Environmental Rhythm

The phenomenon of synchronization has been noted as one of nature's universal themes—something that organizes matter at the subatomic, the galactic, and the biological scale (Strogatz, 2003). The importance of the aforementioned research is that these same dynamical synchronization processes also sustain the informational synchronization of behavior with environmental rhythms. Additional evidence for the power of these processes to organize behavior would be obtained if such synchronization occurred spontaneously between the actor and the environmental rhythm, without awareness or intention.

Some research has been performed in this area to determine whether dynamical entrainment processes are binding such that a

behavioral rhythm is “captured” by an environmental rhythm. In a series of studies, Repp (2004, 2006; Repp & Penel, 2004) has investigated the extent to which a participant's synchronization to an external rhythm is disturbed by distractor rhythms and whether the pattern of rhythmic distraction is evidence for dynamical entrainment or merely correction of perceptual error (i.e., perceptual integration). Using a tapping task, Repp and Penel found that a discrete auditory distractor sequence influenced synchronization with a visual target sequence but that a visual distractor sequence had little influence on synchronization with an auditory target sequence. Further, Repp (2004) found that when an auditory distractor rhythm was present simultaneously with the relevant auditory rhythm for the synchronization task, the pattern of distraction suggested a perceptual integration mechanism. However, when a distractor rhythm was present during a self-paced rhythmic production (using a continuation method), the pattern of distraction suggested a dynamical process of entrainment (Repp, 2006). It is important to note that the latter entrainment phenomenon only occurred when the distractor tempo was close to the tempo of the target (self-paced) rhythm. This result suggests that there is only a small range of frequency differences for which unintentional coordination with an environmental rhythm will occur (Strogatz, 1994).

Other research has demonstrated unintentional dynamical entrainment of postural sway with visual environmental rhythms in so-called moving rooms (Dijkstra, Schöner, & Gielen, 1994; Dijkstra, Schöner, Giese, & Gielen, 1994) or that is haptically created by touching an oscillating bar (Jeka, Oie, Schöner, Dijkstra, & Henson, 1998; Jeka, Schöner, Dijkstra, Ribeiro, & Lackner, 1997). This postural synchronization occurs outside the awareness of participants for low environmental frequencies of oscillation (0.05–0.5 Hz for vision), can be weakened by increasing the distance between a participant and the visual environmental rhythm (Dijkstra, Schöner, & Gielen, 1994), and has been modeled as a forced oscillatory system (Schöner, 1991). Dijkstra, Schöner, Giese, and Gielen (1994) found systematic changes in relative phase lag and stability, which can be interpreted as being consistent with an oscillatory process that has a resonant frequency of about 0.2 Hz and is passively driven by an oscillatory pattern of visual information (Russell et al., 2004). However, at higher frequencies away from the stable resonant tempo, these authors found evidence for a range of variable phase relations indicative of phase entrainment (relative coordination) rather than phase locking (absolute coordination; von Holst, 1939/1973). This and other qualitative properties of the coordination suggest that the generation of postural sway is an active rather than a passive process, such that the inherent frequency of the postural system and damping coefficient are not constant but adapt to the frequency of the visual motion (Giese et al., 1996).

Lastly, evidence for unintentional coordination of a person's movements with environmental rhythms is found in interpersonal interactions, in which the synchronization and mimicry of speech, gestures, and postures of interacting individuals occurs outside of the awareness of the participating individuals. Social psychologists (Bernieri & Rosenthal, 1991; Chartrand & Bargh, 1999) investigating this kind of coordination have been mostly interested in how the quality and quantity of this interpersonal coordination is affected by personality characteristics and social properties (e.g., rapport and other-directedness). However, a few studies have

investigated the informational and dynamical basis of such social synchrony. Shockley, Santana, and Fowler (2003) found unintentional entrainment of postural sway between two individuals who were verbally solving a dyadic puzzle task, demonstrating that verbal information is sufficient to create interactional synchrony of postural sway. Richardson, Marsh, and Schmidt (2005) found that limb movements will tend to become synchronized at relative phase angles near  $0^\circ$  and  $180^\circ$ —as predicted by a coupled oscillator model (Haken et al., 1985)—during a similar dyadic puzzle task, but only when visual information about the other person's limb movements is available; just conversation between the participants did not produce a synchronization of limb movements the way it did for postural sway in Shockley, Santana, and Fowler (2003).

In summary, the above studies suggest that not only do dynamical processes of entrainment operate to synchronize a person's behavior with the environment but also that this entrainment process can occur unintentionally, without awareness. Not surprisingly, the strength of the ensuing unintentional coupling is generally weaker than that of the intentional coupling. For example, in the case of intentional coordination with a sinusoidal stimulus at a moderate frequency, absolute coordination with phase locking can be maintained (Byblow et al., 1995), whereas Richardson et al. (2005) found relative coordination with phase entrainment for unintentional between-person entrainment of limbs. Evidence from postural studies suggests that unintentional postural entrainment can be somewhat stronger than the between-person entrainment of limbs but depends on stimulus amplitude, distance, and frequency (Dijkstra, Schöner, & Gielen, 1994; Dijkstra, Schöner, Giese, & Gielen, 1994).

### Eye Movements as a Constraint on Environmental Coordination

The idea that perceptual systems are exploratory, active, and intrinsically related to action coordinated with the environment has been heralded for some time (e.g., Gibson, 1966, 1979). We need to perceive to move, and we need to move to perceive. There is a significant literature that addresses the importance of active information pickup in haptics (perception of shape: Gibson, 1962), audition (localization of sound: Easton, 1983; Muller & Bovet, 1999), and vision (task-dependent nature of the patterning of saccades: Yarbus, 1967). However, in spite of this research, the motor activity involved in the pickup of perceptual information often goes unnoticed or, at best, is constrained by experimental procedures. As a result, little is known about the effects of the observable motor activity of the perceptual system on assembling ongoing actions. This article addresses this issue by investigating the effects that the observable sensorimotor activity of the eyes during visual tracking has on the coordination of rhythmic limb movements with environmental rhythms. The question is whether such ocular activity needs to be conceptualized as part of the dynamic synchronization process that emerges in the experiment or whether it can be ignored (as it has been).

Past research has noted a high degree of coordination between limb and eye movements. For example, Hollands, Marple-Horvat, Henkes, and Rowan (1995) noted intricate coordination between visual saccades and footfalls in visually guided locomotion: 68% of the saccades to the next footfall location were made while the

foot was still on the ground, and the remaining were completed in the first 300 ms of the swing phase. Other research suggests a strong coupling of saccades with manual reaching or pointing movements. Sailer, Eggert, Ditterich, and Straube (2000) found that the latencies in identical saccade and manual pointing tasks had a similar pattern. In addition, saccades are initiated more quickly, are more accurate (Lunenburger, Kurtz, & Hoffman, 2000), and tend to have higher peak velocity (Snyder, Calton, Dickinson, & Lawrence, 2002) when manual movements are in the same direction as the saccade. Moreover, latency of saccade increased when manual movements were in directions opposite the saccade (Lunenburger et al., 2000). Other research has shown the converse effect—namely, that eye movement pattern influences the execution of limb movements (Henriques & Crawford, 2002; van Donkelaar, 1997).

In other words, there is plenty of evidence that there is intrinsic coupling between limb and eye movements. How might such coupling be affected if eye movements were to be controlled or eliminated? Would intentional entrainment to an environmental rhythm be more difficult and the strength of dynamical entrainment weakened? Would unintentional entrainment to an environmental rhythm become impossible? The two experiments reported below addressed these questions.

### Experiment 1

In this experiment, we investigated the effect of visual tracking and eye movements on unintentional coordination of rhythmic limb movements with a visual stimulus moving in a sinusoidal fashion. Although unintentional coordination with a visual rhythmic stimulus has been found for postural sway, no previous research has demonstrated that rhythmic limb movements become unintentionally entrained to a visual rhythmic stimulus. On the basis of past research that has demonstrated that the spatial relationship between the stimulus and limb movement is important for dynamical entrainment (Wimmers et al., 1992), we used a rhythmic visual stimulus that was moving in a horizontal plane parallel to the participant's limb movements.

To investigate the effect of visual tracking on environmental entrainment, we developed a dual-task paradigm (see Figure 1a) in which participants were required to read letters that appeared on a screen while simultaneously performing a rhythmic motor task (i.e., swinging a hand-held pendulum at a comfortable tempo). We told participants that the purpose of the experiment was to evaluate their reading performance and that the motor task was a distractor. However, we were primarily interested in whether the participants' pendulum swinging would become entrained with the sinusoidally moving stimulus that appeared on the screen. In the visual tracking condition, the letters to be read appeared printed on the moving stimulus (a small square). Consequently, the participants needed to track the stimulus with their eyes to read the letters. In the nontracking condition, the letters to be read appeared in a stationary location just above the moving stimulus, and participants did not have to move their eyes to read the letters (see Figure 1b). In the control condition, the participants read letters that appeared in a stationary location, and there was no moving stimulus visible. We also manipulated the oscillation frequency of the moving stimulus to investigate the strength of the possible entrainment

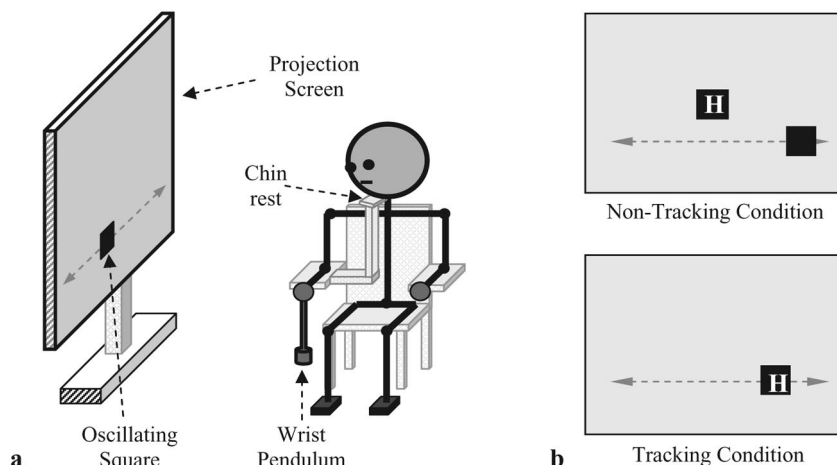


Figure 1. (a) Experimental setup for Experiments 1 and 2. (b) Tracking and nontracking condition displays used for the two experiments.

processes. Stronger entrainment processes would be indicated by entrainment across a larger range of stimulus frequencies.

### Method

**Participants.** Fourteen undergraduates from the University of Connecticut participated in the experiment for partial course credit. All participants had normal vision and were right-hand dominant.

**Materials.** A hand-held pendulum was constructed from a wooden dowel 50 cm long with a 200-g plastic weight attached to its base. The participants swung the pendulum in the sagittal plane using ulnar-radial deviation of the wrist joint. These movements were recorded using an electrogoniometer (Biometrics SG 75; Biometrics, Ltd., Ladysmith, VA) attached on the back of the hand (under the middle knuckle) and 12–15 cm up the forearm. A PC was programmed to record the wrist oscillation time series as well as to create the oscillation of a visual stimulus on the projection screen and display the letters that participants had to read. The letters to be read by the participants appeared approximately every 2 s (2 s plus some random offset between 0 and 999 ms) for 200 ms. The computer-generated displays were projected using an NEC MT850 projector (NEC Visual Systems, Itasca, IL) that was placed on a 1.36-m-high stand positioned 2.46 m away from the screen. The oscillatory stimulus (a 4-cm square occupying  $0.72^\circ$  of visual angle) oscillated horizontally on the screen at the eye level of the participant with an amplitude of 86 cm. Participants sat in a chair positioned parallel to the projection screen. The chair had a forearm support parallel to the ground on the right-hand side and a chin rest platform that assured that the participant's head remained stationary (see Figure 1a). The chair was positioned 1.6 m from the projection screen so that when the participant's head was turned sideways toward the screen and his or her chin rested on the chin rest, the participant's center of gaze was in line with the center of the projection screen and the trajectory of the visual stimulus corresponded to  $14^\circ$  of angular deviation to either side of the participant's center of gaze. A video camera was positioned below the center of the projection screen to record the participant's eye movements during each trial. The camera was focused on the eyes of the participant (the recordings included the participant's eyes, nose,

and bottom section of the forehead) so that we could review whether the participant had followed task instructions—namely, whether the participant tracked the visual stimulus or had a fixed gaze.

**Tasks.** The experiment was split into two sessions: a preliminary task session and an experimental task session. During the preliminary session, participants were required to swing the pendulum while reading letters that appeared in a stationary 4-cm square displayed in the middle of the projection screen. This preliminary task gave a participant the opportunity to experience the dual task of swinging the pendulum while reading the letters and, at the same time, provided a measure of the participant's comfort-mode tempo. There was no oscillating stimulus for this preliminary task.

During the experimental session, participants were required to perform three different tracking tasks: a nontracking task, a tracking task, and a control task (see Figure 1b). For these three tracking conditions, the participants' motor task was always the same—namely, to swing the pendulum at their comfort-mode tempo. For the nontracking task, participants read letters that appeared in a stationary square in the middle of the screen while a moving stimulus square oscillated horizontally just below the letter square. The participants were told to ignore the moving square and to focus their attention on the letters. Hence, it was made clear to participants that during the nontracking task, their eyes had to remain focused on the central stationary square that displayed the letter stimuli and not track the moving stimulus. For the tracking task, the participants also read letters that appeared on the screen; however, the letters appeared on the horizontally oscillating square. Hence, to read the letters, the participants had to track the oscillating square with movements of their eyes. In other words, participants were required to oscillate their eyes from side to side to perform the visual task. The participants were instructed to keep their chin on the chin rest and their head stationary throughout the duration of each trial. For the control task, no oscillating stimulus appeared on the screen as the participants swung the pendulum and read the letters that appeared in a square in the middle of the screen. Although no oscillating stimulus was presented during the control task, the computer program generated an oscillating stimulus time series at one of the three stimulus periods.

The coordination between these control trial stimulus time series and the participants' wrist movements could then be used as an index of chance-level coordination.

For all of the tracking conditions, we manipulated the period of oscillation of the moving stimulus by using the comfort-mode periods and standard deviations from the preliminary session to calculate the appropriate oscillation period of the stimulus for each condition. Specifically, the period of the oscillatory stimulus was either at the comfort-mode period of the participant (set as the average period of six preliminary trials), at the comfort-mode period plus 1 period standard deviation (set as the average period standard deviation of the six preliminary trials), or at the comfort-mode period minus 1 period standard deviation. Past research has demonstrated that individuals reliably swing wrist pendulums at a frequency of oscillation that is slightly faster than the pendulum's physically determined eigenfrequency (Kugler & Turvey, 1987; Russell et al., 2004). This previous research has also demonstrated that an individual's self-selected or comfort-mode period remains stable across time (i.e., across a single trial, a sequence of trials, and sequences of trials separated across days or months; Kugler & Turvey, 1987; Schmidt & Turvey, 1992). The participant's comfort-mode period was also selected as the fundamental stimulus period because even small differences between the frequency of an individual's movement and an environmental rhythm can significantly reduce the possibility of entrainment (Repp, 2006; Schmidt & O'Brien, 1997).

This latter issue was confirmed in a pilot study, in which 25 participants swung a hand-held pendulum at a self-selected tempo while visually tracking an oscillating stimulus that was presented on a projection screen. Five different oscillation periods were used for the stimulus and were proportions of the participant's comfort period—namely, 0.83, 0.91, 1.0, 1.1, or 1.25 times the comfort-mode period. The participant's comfort-mode period was determined as the average comfort-mode period from two pretrials, in which the participant swung the hand-held pendulum. Using cross-spectral coherence (see below for details) as a measure of the coordination between the movement and stimulus time series, we found entrainment to occur only when the stimulus oscillated at the participant's comfort-mode tempo. That is, no unintentional coordination was observed when the stimulus's period was equal to 0.83, 0.91, 1.1, or 1.25 times the participant's comfort-mode period. On the basis of the findings of this pilot study, we decided to use small changes in stimulus frequency that were based on the participants' average standard deviations of period for the current experiment. Not only did a participant's average standard deviation of period provided a circumscribed range of periods, it also provided a period range more likely to be in the movement-stimulus basin of entrainment for each individual participant because it controlled for individual differences in period stability and, hence, adaptability (Newell & Slifkin, 1998; Riley & Turvey, 2002).

*Procedure.* On arrival, the participants were informed that the experiment was investigating multitask performance. Participants were told they would be required to complete a motor task (swinging a pendulum) while verbally identifying letters that appeared on the screen. All rested their right forearm on the arm support. They were first instructed on how to swing the pendulum—namely, to grasp it firmly in the hand and swing it using the wrist joint in a back-and-forward motion. They were told that their task was to

swing the pendulum always at their comfort tempo, "the tempo that you could swing all day if you had to." The participants were then given a chance to explore different tempos in order to identify the "feel" of the comfort tempo.

The experiment consisted of twenty-four 35-s trials. The first 6 trials constituted the preliminary session in which a participant's comfort-mode period was determined. The remaining 18 trials made up the experimental session, the nine different conditions (three tracking and three stimulus periods) presented twice. The order of these conditions in the experimental session was randomized. Throughout the experimental session, the participants were reminded of the task instructions for each trial—this included reminding participants to swing the pendulum at their own self-selected comfort tempo and to maintain that tempo for the entire length of each trial. For all trials (both preliminary and experimental), participants were also instructed to keep their chin in a chin rest platform and their head stationary throughout the length of the trial. The chin rest assured that during the tracking trials participants tracked the oscillating stimulus exclusively by moving their eyes and not their head. Finally, the experimenter manually recorded the number of letters that participants correctly read.

*Design and analysis.* The experiment was a  $3 \times 3$  repeated measures design with variables of tracking (nontracking, tracking, control) and stimulus period (comfort period  $- 1 SD$ , comfort period, comfort period  $+ 1 SD$ ). A number of dependent measures were used to determine whether the coordination between the moving stimulus and wrist was affected by the different conditions. To determine whether the environmental stimulus affected the timing, we calculated the period of oscillation of the wrist as the time between the points of maximum extension (peaks) of the wrist-movement time series. To evaluate the correlation of the wrist movements with the movements of the environmental stimulus, we calculated cross-spectral coherence at the peak frequencies using the wrist and stimulus time series. Coherence measures the degree of coordination between the two time series on a scale from 0 to 1. A coherence of 1 reflects perfect correlation of the movements (absolute synchrony/phase entrainment), and 0 reflects no correlation (no phase entrainment/synchrony; Richardson et al., 2005; Schmidt & O'Brien, 1997). Additionally, to assess the kind of synchronization that emerged, we also evaluated the distributions of relative phase angles formed between the wrist and oscillating stimulus across the conditions. To determine these distributions, we calculated the continuous time series of relative phase for each trial. These relative phase time series were then centered around  $0^\circ$  (i.e., they reflected relative phase angles from  $-180^\circ$  to  $+180^\circ$ ), and the frequency of occurrence of the absolute value of these relative phase angles across nine  $20^\circ$  regions of relative phase (i.e.,  $0^\circ$  to  $20^\circ$ ,  $21^\circ$  to  $40^\circ$ , . . . ,  $161^\circ$  to  $180^\circ$ ) between  $0^\circ$  and  $180^\circ$  was calculated (for more details, see Richardson et al., 2005; Schmidt & O'Brien, 1997). Phase-entrained coordination is indicated by a concentration of relative phase angles in the portions of the distribution near  $0^\circ$  and  $180^\circ$ .

## Results

The first 5 s of each trial was not analyzed so as to eliminate any initial transient coordination. Thus, all analyses were conducted on 30 s of data. The average comfort-mode period and standard deviation for the preliminary trials were 1.163 s and 0.054 s,

respectively. Consequently, the average stimulus periods used were the comfort-mode period (1.163 s), 54 ms slower (1.22 s), and 54 ms faster (1.1 s). The wrist period of oscillation for the 18 experimental trials was submitted to a  $3 \times 3$  analysis of variance (ANOVA). The analysis revealed that the wrist tempo was influenced by the stimulus period,  $F(2, 26) = 3.74, p < .05$ . The wrist period increased as the stimulus period increased (1.130, 1.142, and 1.149 s). Neither tracking nor the Stimulus Period  $\times$  Tracking interaction was significant (both  $ps > .40$ ). Because one would expect that the wrist period would not change across stimulus tempos for the control condition (because the oscillating stimulus was not visible), we performed a simple effects analysis. As expected, this analysis revealed a significant change of the wrist period for the tracking condition,  $F(2, 12) = 5.39, p < .05$  (see Figure 2a) but not for either the nontracking or the control condition (both  $ps > .05$ ). No significant effects were found when period standard deviation was submitted to a similar ANOVA. The average standard deviation for all conditions (0.044 s) was not significantly different from that of the preliminary trials (0.054 s;  $p > .05$ ).

To determine whether the correlation of the wrist and stimulus movements was affected by the conditions, we standardized the cross-spectral coherence values using a Fisher  $z$  transformation and then submitted them to a  $3 \times 3$  ANOVA. The analysis revealed a main effect for tracking,  $F(2, 26) = 7.02, p < .01$  (see Figure 2b). Post hoc comparisons found that the magnitude of coherence was greater for the tracking condition (.45) than for the nontracking (.26) and control (.26) conditions ( $ps < .05$  for both comparisons), whereas the control and nontracking conditions did not differ ( $p > .05$ ). This pattern of results suggests that above-chance-level correlation between the participant's movements and the stimulus occurred in the tracking condition, whereas only chance-level correlation occurred in the nontracking condition. The analysis also yielded a significant effect of stimulus period,  $F(2, 26) = 3.36, p < .05$ . The coherence increased from the slower (.20) to the comfort (.37) stimulus period ( $p < .05$ ), but the coherence did not differ for comfort and faster stimulus period (.39) conditions ( $p > .05$ ). The Tracking  $\times$  Stimulus Period interaction was not significant ( $p > .05$ ).

Another way to investigate how the rhythmic movements of the wrist became entrained to the oscillating visual stimulus is to evaluate the distribution of relative phase angles created between the two movements. A flat distribution of relative phase angles across all phase regions would suggest no coordination occurred between the two oscillations, whereas a concentration of phase angles at specific regions would indicate that phase entrainment had occurred. Further, a concentration of phase angles near  $0^\circ$  or  $180^\circ$  would suggest that entrainment was in the stable modes of a coupled oscillatory dynamic (Kelso & Ding, 1994; Schmidt & O'Brien, 1997). The distribution of relative phase angles across the nine phase regions was submitted to a  $3 \times 3 \times 9$  ANOVA with the factors of tracking, stimulus period, and phase region. The analysis revealed a significant effect of phase region,  $F(8, 104) = 8.53, p < .001$ , and a Tracking  $\times$  Phase Region interaction,  $F(16, 208) = 6.94, p < .001$ . As shown in Figure 2c, the nontracking and tracking conditions showed a U-shaped distribution, with greater concentrations of relative phase near  $0^\circ$  and  $180^\circ$ , whereas the control condition yielded a flat distribution. The increases near  $0^\circ$  and  $180^\circ$  were tested by post hoc  $t$  tests for the nontracking and

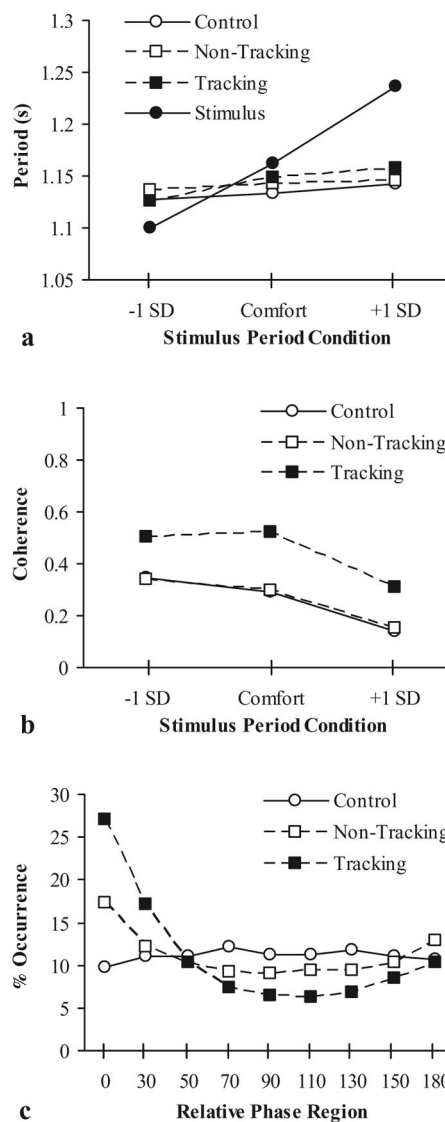


Figure 2. (a) Effect of stimulus tempo on pendulum period of oscillation for the tracking, nontracking, and control conditions in Experiment 1. Period of the stimulus is also displayed for comparison purposes. (b) Average coherence between the pendulum and oscillating stimulus for tracking and nontracking conditions across the different stimulus tempos. (c) Distributions of relative phase angles as a function of the nine  $20^\circ$  regions of relative phase (i.e.,  $0^\circ$  to  $20^\circ$ ,  $21^\circ$  to  $40^\circ$ , . . . ,  $161^\circ$  to  $180^\circ$ ) for tracking and nontracking conditions versus the control condition.

tracking conditions. For the nontracking condition, the distributions of phase angles in the middle phase regions ( $80^\circ$ – $100^\circ$  and  $100^\circ$ – $120^\circ$ ) were significantly different from the concentrations in the region near  $0^\circ$  ( $p < .05$ ), but they were not different from the concentrations near  $180^\circ$ . For the tracking condition, the distributions of phase angles in the middle phase regions ( $100^\circ$ – $120^\circ$  and  $120^\circ$ – $140^\circ$ ) were significantly different from both the concentration in the region near  $0^\circ$  and that in the region near  $180^\circ$  ( $p < .05$ ). Thus, phase entrainment seemed to occur for both the nontracking and tracking conditions, but the entrainment seemed to be

stronger for tracking. Further, nontracking only produced inphase entrainment ( $0^\circ$ ), whereas tracking produced inphase ( $0^\circ$ ) and antiphase ( $180^\circ$ ) entrainment.

### Discussion

This experiment investigated whether unintentional entrainment would occur between the rhythmic movements produced by a participant and a visual oscillating stimulus in the environment. We manipulated the tempo of the oscillating stimulus and whether the participant was required to visually track the stimulus with oscillatory eye movements. In brief, the results indicate that unintentional coordination did occur for both tracking and nontracking and for the three stimulus periods but that entrainment was stronger when the stimulus was tracked with the eyes and when the stimulus period was equal to a participant's comfort period. For tracking but not for nontracking, the stimulus period analysis revealed evidence of frequency entrainment, and the coherence analysis found significantly above-chance correlation between the stimulus and the participant's movements. Because phase-locked intentional coordination has coherence values near 1.0 (see Experiment 2), and unintentional coordination has coherence values between .33 and .56 (Richardson et al., 2005; Schmidt & O'Brien, 1997), we can conclude that in this experiment a weak relative coordination was occurring between the pendulum movement and the stimulus. Perhaps the best evidence for unintentional entrainment is provided by the concentration of relative phase angles near  $0^\circ$  and  $180^\circ$  for both tracking and nontracking. Such U-shaped distributions are indicative of the stable modes for a coupled oscillatory dynamic and suggest a tendency for the participant's movements to be either in inphase or in antiphase with the visual stimulus. However, as in past research (Repp, 2006; Richardson et al., 2005), the observed relative phases are indicative of relative coordination rather than phase locking.

The results of this experiment demonstrate that unintentional entrainment occurs between an oscillating environmental stimulus and a person's rhythmic movements and that this entrainment is stronger if the stimulus is tracked with the eyes but still present if it is not. These results are consistent with past research that has found facilitation of both limb movements and saccades when they are performed together (van Donkelaar, Siu, & Walterschied, 2004). What the limits of the tempo range for unintentional entrainment are, and whether the strength of the entrainment depends on where in the range the tempos reside, remains to be determined. If the two oscillations were to behave as physically coupled oscillators, we would predict a decrease in entrainment strength as the tempos of the stimulus deviate from tempo of the wrist. An experiment that manipulates the tempos of the stimulus in fine gradations could determine limits of the range of entrainment by finding those tempos at which the coherence is equivalent to chance or at which the relative phase distribution becomes flat. Another question is whether this range of entrainment depends on the variability exhibited by the participant's comfort-mode oscillation. In the present experiment, the faster and slower tempo conditions were scaled to the variability of the participant in the preliminary trials. The question of how an individual's range of entrainment is related to the magnitude of his or her own variability remains to be tested empirically. Specifically, future research should examine whether individual differences in the range of

entrainment are perhaps related to the size of standard deviation of an individual's comfort period.

Also, the relationship between visual tracking and unintentional entrainment needs to be further explored. Of interest are whether the amount of entrainment increases with the amount of tracking and whether the influence of tracking depends on whether the tracking is continuous or intermittent. The amount of tracking can be measured using an eye tracker, and different experimental conditions could be used to manipulate the intermittency of tracking. These issues raise the question of whether eye movements in the present experiment were really controlled in the nontracking condition. A postexperimental review of the video-recorded eye movements of the participants revealed large qualitative differences between the eye movements in the tracking and nontracking conditions and no observable difference between the eye movements in the nontracking and control conditions. For the vast majority of the trials in these latter conditions, the recordings revealed that participants' eyes remained stationary, focused on the center of the projection screen. However, the participants' eye movements for the tracking trials were continuously oscillating back and forth, focused on the center of the screen. Although it is clear from the video records that the eye movements were different for the tracking and nontracking conditions, only by measuring the eye movements with an eye tracker would we be able to test whether the nontracking condition had some degree of eye movement related to unintentional entrainment and whether the strength of entrainment in the tracking condition depended on how the eyes moved.

The results of this experiment have some ramifications. First, they verify that the movements of the visual system are coupled to movements of the limbs (van Donkelaar et al., 2004). Although much research has demonstrated that two rhythmic limb movements are necessarily coupled and may "interfere" with or "facilitate" one another (Franz, Zelaznik, Swinnen, & Walter, 2001), a "coupling" dependency between rhythmic eye movements and rhythmic limb movements has not heretofore been demonstrated. Second, the results demonstrate that interactions between the movements of the eyes and limbs can mediate the coordination of limb movements with the movement of environmental stimuli. If we follow an object with our eyes and our limb movements are coupled to our eye movements, then our limbs will tend to move like the object in the environment. This mediational process may promote the mimicry and synchrony found in natural interpersonal interactions (e.g., Bernieri & Rosenthal, 1991). Finally, the fact that some weaker unintentional coordination occurs with no ocular movements suggests that unintentional coordination between an actor and an environmental stimulus is not fully explained by an intrinsic coupling between the eyes and the limbs. It seems that the coupling of the eyes and wrist facilitates the process of entrainment of the wrist and the visual stimulus but is not necessary to create it. One possible explanation of the relation between the tracking and nontracking results is that the strength of the coupling between the environmental stimulus and the wrist movements depends on the richness of the information that participants have about the environmental stimulus and on their having richer information about the movement of the object when they are tracking it. One might suppose that the global optic flow created during tracking might make the motion information more salient than the local optic flow created just by the stimulus motion in the nontracking condition. However, the homogeneity of the background behind the stimulus would mitigate any global optic flow infor-

mation. Alternatively, the visual information gathered by the eyes during tracking may be enriched by proprioceptive haptic feedback or efferent feedforward activity.

A way to test whether tracking a stimulus with the eyes increases the strength of the oscillatory dynamic is to have participants *intentionally* coordinate their movements with the stimulus while tracking the object with their eyes or not and measure the stability of the ensuing coordination. One should see a greater stability of the coordination during tracking than during nontracking if the strength of the coupling is increased. Such an experiment would also verify that a dynamic between rhythmic limb movements and an oscillating environmental stimulus does indeed exist by determining whether the patterning of the relative phasing and its stability are commensurate with the predictions of a coupled oscillatory model. In particular, inphase coordination should be more stable than antiphase, the relative phase lag should depend on the difference in stimulus tempo from the comfort-mode tempo, and the relative phase variability should increase with increases in tempo (Russell et al., 2004; Schmidt & Turvey, 1994). Such an investigation was performed in Experiment 2.

## Experiment 2

### Method

**Participants.** Fifteen undergraduates from the University of Connecticut participated in the experiment for partial course credit. All participants had normal vision and were right-hand dominant. The data from 5 participants were not used because an incorrect setting of the computer monitor's refresh rate increased the difficulty of the coordination task.

**Materials.** The same materials and experimental setup as in Experiment 1 were used for Experiment 2, with the exception that for some participants a Dell 4100MP projector was used instead of the NEC MT850 used for the previous experiment. The two projectors performed identically.

**Task and procedure.** All participants were seated in a chair parallel to the screen. Instead of maintaining a comfort-mode tempo through each trial of the experiment, the participant's task was to intentionally move at the same tempo as the oscillating stimulus in either an inphase or an antiphase mode of coordination. The experiment consisted of twenty-eight 35-s trials. The first 4 trials were preliminary and were used to measure a participant's comfort tempo while reading letters that appeared on the screen. The remaining 24 experimental trials were either nontracking or tracking trials. The displays for the nontracking and tracking conditions as well as the manipulation of tempo of the oscillating stimulus (comfort-mode period  $- 1$  period *SD*, comfort-mode period, or comfort mode period  $+ 1$  period *SD*) were identical to those of Experiment 1. The mode of coordination was manipulated for the experimental trials as well. Half of the trials were inphase and half were antiphase.

**Design and analysis.** The experiment had a  $2 \times 3 \times 2$  repeated measures design with factors of tracking (nontracking, tracking), stimulus period (comfort period  $- 1$  *SD*, comfort period, comfort period  $+ 1$  *SD*), and coordination mode (inphase, antiphase). The 12 different conditions were presented twice. The order of the conditions was randomized. The period of oscillation of the wrist and its standard deviation, cross-spectral coherence,

relative phase lag (deviation from intended coordination mode), and relative phase standard deviation were used as dependent measures.

### Results

The first 10 s of each trial were not analyzed so as to eliminate any initial transient coordination.<sup>1</sup> Thus, all analyses were conducted on 25 s of data. The average comfort-mode period and standard deviation for the preliminary trials were 1.21 s and 0.048 s, respectively. The wrist period of oscillation for the 18 experimental trials was submitted to a  $2 \times 3 \times 2$  ANOVA. The analysis revealed, as expected, that the wrist tempo changed with the stimulus period,  $F(2, 18) = 106.36$ ,  $p < .05$ . As can be seen in Figure 3a, on average participants matched the stimulus period very well. Effects of tracking and coordination mode were not significant. A similar analysis performed on period standard deviation, however, found a significant main effect for tracking,  $F(1, 9) = 14.10$ ,  $p < .001$ ; a marginally significant main effect of coordination mode,  $F(1, 9) = 4.6$ ,  $p = .06$ ; but no effect of stimulus period,  $F(2, 18) = 0.27$ ,  $p > .05$ . Although the absolute differences in magnitude were not very large, periodic timing was more variable during the nontracking (0.039 s) than during the tracking (0.033 s) condition and more variable for the antiphase (0.038 s) than for the inphase (0.034 s) coordination mode.

The degree to which the coordination between the stimulus and wrist movements was affected by the conditions was evaluated with an ANOVA on cross-spectral coherence. As in Experiment 1, the coherence values were standardized for the analysis using a Fisher  $z$  transformation. The analysis yielded main effects of stimulus period,  $F(2, 18) = 4.91$ ,  $p < .05$ ; tracking,  $F(1, 9) = 11.58$ ,  $p < .01$ ; and coordination mode,  $F(1, 9) = 6.30$ ,  $p < .05$ . The coherence increased as the stimulus period increased (.945, .958 and .964), it was greater for tracking (.963) than for nontracking (.948), and it was greater for the inphase (.962) than for the antiphase (.949) coordination mode. The mean coherence magnitudes were twice as large as the largest values observed in Experiment 1 and denote correlations indicative of phase-locked absolute coordination rather than the phase-entrained relative coordination of the previous experiment.

Because the coordination was phase locked, the phasing of the wrist movements with respect to the moving stimulus was evaluated not in terms of the distribution of relative phase angles but in terms of the relative phase standard deviation and mean deviation from intended relative phase. The standard deviation of relative phase can be used in addition to the cross-spectral coherence to evaluate the degree of coordination between the wrist movements and the oscillating stimulus. An ANOVA revealed main effects of stimulus period,  $F(2, 18) = 3.63$ ,  $p < .05$ ; tracking,  $F(1, 9) = 9.96$ ,  $p < .05$ ; and coordination mode,  $F(1, 9) = 8.84$ ,  $p < .05$ . The relative phase standard deviation decreased as the stimulus period increased (17.79°, 15.48°, and 14.93°), it was greater for nontrack-

<sup>1</sup> The first 10 s of each trial was extracted to remove transients in Experiment 2, compared with only 5 s in Experiment 1, because the time required by the participants in Experiment 2 to establish inphase or antiphase coordination was sometimes longer than 5 s but always less than 10 s, whereas the time required by participants in Experiment 1 to produce a stable period of movement was always less than 5 s.

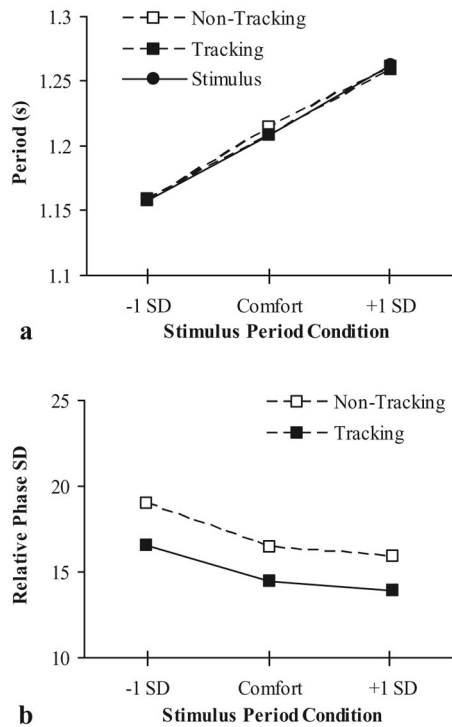


Figure 3. (a) Effect of stimulus tempo condition on pendulum period of oscillation for the tracking and nontracking conditions in Experiment 2. Period of the stimulus is also displayed for comparison purposes. (b) The relative phase standard deviations for the tracking and nontracking conditions across the stimulus period conditions.

ing ( $17.15^\circ$ ) than for tracking ( $14.97^\circ$ ), and it was greater for the antiphase ( $17.25^\circ$ ) than for the inphase ( $14.88^\circ$ ) coordination mode. A comparison of the relative phase standard deviations across the stimulus frequencies for the tracking and nontracking conditions is depicted in Figure 3b. The magnitude of variability and of differences between conditions (coordination modes and tempo) were the same as previously observed for bimanual coordination (Schmidt et al., 1998). No other effects were found to be significant.

The deviation from intended relative phase indexes the lag-lead relation between wrist and the stimulus (negative = *hand leads*, positive = *stimulus leads*) as well as how closely the relative phasing approximates  $0^\circ$  and  $180^\circ$  for inphase and antiphase coordination, respectively. An ANOVA performed on the deviation from intended phase found a main effect of stimulus period,  $F(2, 18) = 14.56, p < .001$ , but no main effects or interactions of tracking or coordination mode. The significant main effect for stimulus period indicates that when the stimulus period was at comfort mode, the deviation from  $0^\circ$  or  $180^\circ$  was close to zero ( $0.87^\circ$ ); when it was faster than comfort mode, the wrist lagged behind the stimulus in the cycle ( $-10.71^\circ$ ); and when it was slower than comfort mode, the wrist led the stimulus in the cycle ( $6.60^\circ$ ).

### Discussion

The results of this experiment are consistent with previous research that has found that the intentional coordination between a

participant's wrist movements and the oscillating environmental stimulus is governed by a coupled oscillatory dynamic. First, antiphase coordination was found to be more variable than inphase coordination by the indices of cross-spectral coherence and relative phase variability (Buekers et al., 2000; Liao & Jagacinski, 2000). Second, the wrist led the visual stimulus in its cycle when it was made to oscillate more slowly than its comfort tempo, and it lagged behind the stimulus in its cycle when it was made to oscillate more quickly than its comfort tempo (Russell et al., 2004; Russell & Sternad, 2001). These predictions stem directly from mathematical coupled oscillator models (e.g., Haken et al., 1985). Two features of the results do not accord with previous research. First, both the cross-spectral coherence and relative phase variability suggest that the stability of the coordination increased as the period of oscillation increased. Although slower tempos have been found to increase the strength of the coupled oscillator dynamic (Haken et al., 1985), which would decrease variability, previous research (e.g., Russell et al., 2004) has found an increase of phase standard deviation for oscillation tempos different from the comfort tempo (faster or slower). Additionally, we did not find greater deviations from intended phase for the antiphase mode than for the inphase mode, as was found previously (Amazeen et al., 1995; Buekers et al., 2000; Liao & Jagacinski, 2000). The lack of replication of both of these findings may be due to the fact that the deviation from comfort-mode period that we were using was relatively small (only  $+50$  ms on average) compared with that used in other studies. That is, the magnitude of detuning used in the current experiment may have been too small for the effects of deviation from comfort mode on the variability of movement and phase lag to be seen.

More important, Experiment 2 also addressed how the visual tracking of the stimulus affects intentional person-environment entrainment. It revealed that the visual tracking of the stimulus increases the stability of coordination with the oscillating visual stimulus. Not only did the variability of timing and relative phasing decrease, but the correlation of the wrist and stimulus movements (as measured by coherence) increased as well. These results support the conclusion that the greater unintentional coordination observed in Experiment 1 for the tracking conditions was a result of a stronger coupled oscillatory dynamic when the eyes were tracking the stimulus. As in Experiment 1, a postexperimental review of the video recordings of the participant's eyes revealed a large qualitative difference between the eye movements in the tracking and nontracking conditions. Specifically, participants' eye movements for the tracking trials were focused on the projection screen, continuously oscillating back and forth, whereas participants' eye movements for the nontracking and control trials remained stationary, focused on the center of the projection screen.

The results of Experiment 2 also relate to recent research that suggests that the coupling of human rhythmic movement generally (intrapersonal or between a person and a rhythmic environmental stimulus) has a perceptual basis (Bingham, 2004; Mechsner, Kerzel, Knoblich, & Prinz, 2001; Wilson et al., 2005). This research demonstrates that  $180^\circ$  and even  $90^\circ$  relative phase between two limbs or between a limb and an environmental stimulus are made more stable if a target visual feedback of  $0^\circ$  relative phase is used. The implication of these results is that the difficulty with non- $0^\circ$  phase relations may be a result of the inability to resolve perceptual information needed to establish these coordinations. The

present results suggest that the activity of the eyes in perceptual pickup may be an uncontrolled variable in this research.

Finally, although the current results are consistent with those of Experiment 1, one could argue that the difference in the stability of the coordination observed for the tracking and nontracking conditions in the current experiment was a result of a difference in cognitive load or task demands. It is possible that the entrainment was weaker for the nontracking condition compared with the tracking condition because the nontracking condition required participants to suppress the eye movements that would typically occur when they were intentionally coordinating with a visual rhythm. In other words, it is not clear whether the nontracking condition resulted in less stable coordination because participants did not track the stimulus with their eyes or because the fixation task was more demanding and *interfered* with the task of coordinating with the moving stimulus. It is interesting to note that recent research has demonstrated that increased cognitive activity or task demands decrease the stability of rhythmic coordination by increasing the magnitude of the stochastic noise that influences movement stability (Pellecchia, Shockley & Turvey, 2005; Shockley & Turvey, 2005; see also Richardson, 2005; Richardson et al., 2005). Future research could therefore investigate whether the difference in the stability of the two conditions is a result of a difference in cognitive load by determining whether the magnitude of stochastic noise is different for the tracking and nontracking conditions.

### Conclusions

The current study emphasizes the importance of examining the activity of the perceptual system in detecting information for the production of rhythmic coordination and, in particular, how such activity mediates the strength of rhythmic environmental coordination. More specifically, the two experiments reported here demonstrate that visual tracking strengthens the coupling between rhythmic limb movements and an environmental periodic event. In other words, the magnitude of unintentional entrainment, as well as the stability of intentional coordination, is partially determined by whether or not the movement of an environmental stimulus is tracked by movement of the eyes.

Finding an inherent relationship between the patterning of rhythmic eye and limb movements suggests that the visual system's activity needs to be conceptualized as part of the dynamic synchronization that occurs between the environmental rhythms and rhythmic limb movements. How perceptual system activity should be incorporated in dynamic models of intentional and unintentional environmental coordination, however, still remains to be seen and may require a dramatic restructuring of such models (Bingham, 2004; Russell & Sternad, 2001).

Although visual tracking increased the strength of the coupling that constrains the unintentional and intentional coordination studied here, it is important to appreciate that the current results are consistent with previous research examining environmental coordination (e.g., Amazeen et al., 1995; Liao & Jagacinski, 2000; Repp, 2004, 2006; Repp & Penel, 2004; Russell et al., 2004; Russell & Sternad, 2001) and that this was true even when there was no visual tracking. Consequently, the current study provides further evidence that coordinating with an environmental stimulus, both intentionally and unintentionally, is constrained by dynamical processes of entrainment. Moreover, the increased magnitude and stability of the rhythmic entrainment that resulted when partici-

pants coordinated their eye movements with the oscillating stimulus underscores the intrinsic link between perceiving and acting (Gibson, 1966, 1979). Accordingly, one must examine both the perceptual activities and the motor activities that emerge during rhythmic coordination to fully understand the dynamic organization of behavior (Bingham, 2004; Kelso, 1995; Knoblich & Flach, 2001; Kugler & Turvey, 1987; Mechsner et al., 2001; Shaw & Kinsella-Shaw, 1988; Turvey, 1990).

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Received August 4, 2005

Revision received August 17, 2006

Accepted August 21, 2006 ■