RESEARCH ARTICLE

Deviations from mirroring in interpersonal multifrequency coordination when visual information is occluded

Jamie C. Gorman[1] · Polemnia G. Amazeen[2] · Michael J. Crites[3] · Christina L. Gipson[1]

Abstract In activities such as dancing and sports, people synchronize behaviors in many different ways. Synchronization between people has traditionally been characterized as either perfect mirroring (1:1 in-phase synchronization, spontaneous synchrony, and mimicry) or reflectional mirroring (1:1 antiphase synchronization), but most activities require partners to synchronize more complicated patterns. We asked visually coupled dyads to coordinate finger movements to perform multifrequency ratios (1:1, 2:1, 3:1, 4:1, and 5:1). Because these patterns are coordinated across and not just within individual physiological and motor systems, we based our predictions on frequency-locking dynamics, which is a general coordination principle that is not limited to physiological explanations. Twenty dyads performed five multifrequency ratios under three levels of visual coupling, with half using a subcritical visual information update rate. The dynamical principle was supported, such that multifrequency performance tends to abide by the strictures of frequency locking. However, these constraints are relaxed if the visual information rate is beyond the critical information update rate. An analysis of turning points in the oscillatory finger movements suggested that dyads did not rely on this visual information to stabilize coordination. How the laboratory findings align with naturalistic observations of multifrequency performance in actual sports teams (Double Dutch) is discussed. Frequency-locking accounts not only for the human propensity for perfect mirroring but also for variations in performance when dyads deviate from mirroring.

Introduction

Like entropy or gravity, synchronization is a force of nature that governs the behavior of systems from fireflies to planets (Strogatz 2003). This force often manifests itself in humans as an overwhelming tendency to mirror each other. Mirroring is the simplest form of synchronization (a 1:1 movement relation) that is commonly observed in human interactions. In social interactions, for example, this force may play a role in the chameleon effect, wherein people unconsciously mirror the movements of others (Chartand and Bargh 1999). Even in simple rhythmic tasks, in-phase or symmetric coordination (perfect mirroring) is most common (Amazeen et al. 1998; Kelso 1995) and occurs spontaneously during both intentional and unintentional interpersonal coordination (Ouiller et al. 2008; Richardson et al. 2007; Varlet and Richardson 2015). However, there are many activities—such as dancing or playing sports— that require people to coordinate more complicated, non-mirroring patterns. In this study, we investigate how dyads coordinate across perceptual channels to perform rhythmic multifrequency patterns in which participants synchronize movements whose frequencies differ (e.g., 2:1 or 3:1). In particular, we seek to determine the role visual coupling mechanisms play in interpersonal multifrequency coordination.

✉ Jamie C. Gorman
jamie.gorman@gatech.edu

[1] School of Psychology, Georgia Institute of Technology, 654 Cherry St. NW, Atlanta, GA 30332, USA

[2] Arizona State University, Tempe, AZ, USA

[3] Texas Tech University, Lubbock, TX, USA

⚫ Springer

Empirical underpinnings of interpersonal multifrequency coordination

An everyday example that illustrates the necessity of coordinating non-mirroring movements in the individual is the act of tying one's shoelaces. Gorman and Crites (2015) instructed participants to tie an "experimental shoe" as quickly as possible and measured synchronization between their hands. They found that the ability to move the hands independently (to not mirror) is fundamental to tying and is presumably practiced from an early age (Albert and Ivry 2009). However, in unpracticed, interpersonal tying (with each person handling one lace), the spontaneous tendency to mirror overwhelmed the requirement for differently timed synchronization and performance suffered. Although participants intended to produce movement patterns characteristic of individual tying, in a novel interpersonal setting, the need to visually couple their movements was sufficiently strong to induce mirroring between their hands.

Indeed, hundreds of experiments on individuals have found an overwhelming tendency to produce mirror patterns between their fingers when the only requirement is to rhythmically oscillate their left and right index fingers together, either up-down or left–right (Kelso 1984; Amazeen et al. 1998). The most common patterns are in-phase (perfect mirroring) and antiphase (reflectional mirroring), the latter of which is performed less often and with less stability. Other patterns, characterized by some phase offset, require extensive practice for stabilization to occur (Amazeen 2002; Fontaine et al. 1997; Lee et al. 1995; Swinnen et al. 1997; Tuller and Kelso 1989; Yamanishi et al. 1980; Zanone and Kelso 1992a, b, 1997). Similarly, patterns in which the oscillators are in a multifrequency relation, for example, 2:1 or 3:1, require practice or visual/acoustic aid to be performed stably (Amazeen et al. 2001; Gonzalez et al. 2010, 2014; Hessler et al. 2010; Mechsner et al. 2001; Peper et al. 1995).

However, there is a growing body of research that demonstrates this preference in interpersonal coordination as well, in which movements are coupled visually or through some other perceptual channel, which can be understood using coupled oscillator theory (Amazeen et al. 1995; Gipson et al. 2016; Ouiller et al. 2008; Schmidt et al. 1990; Richardson et al. 2007). For example, Ouiller et al. (2008) found that visual coupling (being able to see the other person's hand) is sufficient to induce spontaneous 1:1 in-phase synchronization (perfect mirroring) between dyads' finger oscillations. However, the role of perceptual coupling in interpersonal multifrequency coordination is relatively unexplored. In this study, we control dyads' access to visual information to demonstrate how perceptual coupling modulates intentional multifrequency performance. Given that interpersonal multifrequency performance is

coordinated across and not just within individual physiological and motor systems, we based our predictions on frequency locking, which is a general coordination principle that is not limited to physiological and motor explanations within the body.

Frequency locking and interpersonal dynamics

Frequency locking describes the stability of any ratio, p:q (where p and q are integers), where one oscillator (here, a finger) performs p cycles for every q cycles of another oscillator (another person's finger). Frequency locking is ideal for modeling movement relations because it identifies regions of stable performance for coupled oscillators moving in any frequency relation (Bak 1986; Pikovsky et al. 2001). Frequency locking governs the behavior of coupled physical, chemical, and biological oscillators (Glazier and Libchaber 1988), but its applicability to interpersonal coordination is unknown. We focus on empirical predictions from a two-frequency resonance model (Peper et al. 1995) that can be understood using two graphical representations called the Arnold tongues and Farey tree (Fig. 1).

Arnold tongues (Fig. 1a) identify regions of stable performance (black tongues) as a function of two parameters: the ratio of uncoupled frequencies (Ω), often manipulated in experiments as the intended frequency ratio, and coupling strength (K) between the oscillators. An infinite number of tongues exist between $\Omega = 0$ and $\Omega = 1$, and predictions can be made about all of them, although most ratios are too unstable to be performed. The combined motion of coupled oscillators is periodic and closely follows the Farey sequence (Fig. 1b), which we use to guide selection of specific ratios for testing.

Performance stability is related to tongue width and Farey level, such that performance of some ratios (e.g., 2:1) is predicted to be more stable (less variable) than others (e.g., 4:1). Notice also that tongue width increases as coupling strength increases. We will test the hypothesis that coupling strength can be operationalized in interpersonal multifrequency coordination as visual information exchange to control the "tongue width" of any ratio (i.e., accuracy and stability of multifrequency performance). To test that hypothesis, we manipulate the amount of visual information exchange (K) between a dyad performing different intended multifrequency ratios (Ω) by periodically occluding their vision. We manipulate also rate of visual occlusion to examine these dynamics in the context of an inherent characteristic of the visual system, namely, the tendency to "fill in" missing information when there are small versus large gaps in the visual stream.

In addition, research on perceptual coupling of movement to an oscillatory stimulus (here, another person's finger movements) has shown the importance of tracking with
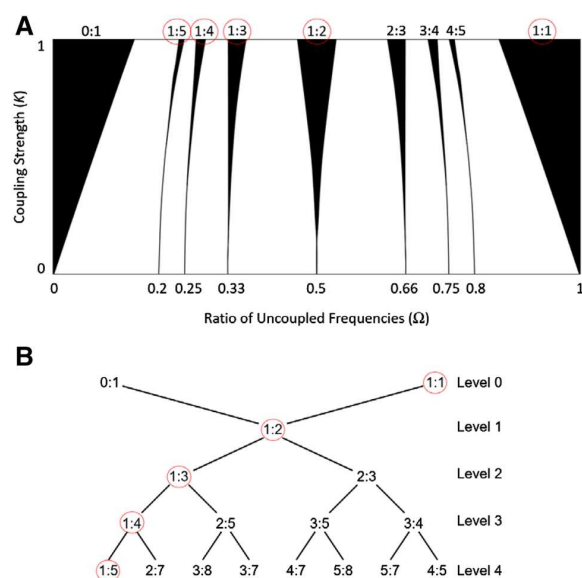
Fig. 1 a The *black* Arnold tongues represent the periodic behavior of coupled oscillators in an iterated circle map ($\theta_{n+1} = \theta_n + \Omega - K/2\pi \times \sin[2\pi\theta_n]$; θ = phase of oscillation), a mathematical model of the interpersonal behavior examined in this study. The width of the Arnold tongues corresponds to predicted stability of frequency ratios as a function of the intended ratio (Ω) and coupling strength (K) between coupled oscillators. **b** The relative stability of ratios is depicted in the Farey tree, where higher levels correspond to less stable ratios. For ease of interpretation, we assume that whole number ratios (1:1, 2:1, 3:1, etc.) correspond to fractional ratios (1:1, 1:2, 1:3, etc.) in terms of relative pattern stability. "Simple" ratios, of which mirroring (1:1) is predicted to be the most stable, are *circled* because they are specifically tested (1:1, 2:1, 3:1, etc., up to Farey Level 4) in this study

the eyes when the stimulus is occluded (Hajnal et al. 2009). By occluding different phase locations of the stimulus, this research demonstrates how "turning points" (i.e., when the stimulus is at either the peak or the trough of its cycle) can provide privileged visual information that ensures stable coordination during intentional synchronization. This suggests that intentionally coordinating dyads may be able to stabilize multifrequency performance by adjusting their turning points to coincide with un-occluded portions of the visual stream. To test for this possibility, we measure the proportion of turning points that occur during un-occluded portions of participants' visual stream. If dyads do adjust their turning points to facilitate coordination, then we expect a higher-than-random proportion of turning points to fall within the un-occluded portion of participants' visual stream. Alternatively, visual tracking may facilitate coordination by increasing the overall amount of visual information that is picked up, rather than privileged turning points (Varlet et al. 2015). If coordination accuracy and stability depends on amount of occlusion and not the use of

turning points, then it may provide support for this second viewpoint.

The current study

According to the model, intended ratio (Ω) and coupling strength (K) control multifrequency performance. In terms of accuracy and stability (variability) of human performance, those model predictions have been supported in experiments on individuals' finger oscillations using drummers (Peper et al. 1995), novice participants (deGuzman and Kelso 1991; Treffner and Turvey 1993), in motor-respiratory coordination (Amazeen et al. 2001; Hessler and Amazeen 2014; Hessler et al. 2010), and in spontaneous coordination between participants and stimuli (Washburn et al. 2014). Model predictions have even been shown to constrain visual perception of multifrequency ratios (Gonzales et al. 2010). However, these frequency-locking dynamics have never been tested on intentional performance of frequency ratios in visually coupled dyads.

Method

Participants

Forty undergraduates (20 dyads) from Texas Tech University participated for partial course credit. The study complied with the principles of the Helsinki Declaration and was approved by the Institutional Review Board of Texas Tech University. Participants' mean age was $M = 20.05$ (SD = 3.11), and 57.5% were female. Four dyads were all male; seven were all female; and nine were mixed-gender. One dyad reported knowing each other (classmates) prior to the experiment. All participants were required to be right-handed with normal or corrected-to-normal vision and hearing.

Apparatus

Participants sat facing each other with their right elbow resting on a table and oscillated their right index finger by flexing and extending around the first metacapophalangeal joint (Fig. 2). Participants sat at separate tables situated so as not to be touching so that participants could not couple via haptic information. Participants gripped a ½″ diameter, 6″ long PVC pipe with their other fingers and thumb to ensure movement of their index finger only. The pipe was raised 6″ above the surface of the table, and the experimenter adjusted the arm rest for each participant to ensure comfortable positioning.

Finger oscillation data were collected using an eight-camera Vicon MX-T10 optical tracking system running

Fig. 2 Apparatus and hand placement

Nexus software (100 Hz). Data were collected from 14 mm reflective markers attached to rubber rings that participants wore on the end of the right index finger. To remove unwanted reflections, all surfaces were covered with either black cloth or black tape.

Participants wore liquid–crystal visual occlusion goggles (PLATO spectacles; Translucent Technologies) throughout the experiment to manipulate the amount and rate of visual information that they had about their partner's movements. The goggles occluded vision by cycling between opaque and translucent. Amount of visual information was manipulated by controlling the percentage of each cycle that goggles were opaque. Rate of visual information was manipulated by controlling the length of the period of each opaque/translucent cycle.

Experiment design

Dyads performed five simple frequency ratios (1:1; 2:1; 3:1; 4:1; 5:1) corresponding to five levels of a within-subjects variable, Intended Ratio, representing the Farey tree levels shown in Fig. 1b. Although the two-frequency resonance model covers an infinite number of frequency ratios, we focused on simple ratios because of the ease with which participants can understand them compared to "complex" ratios (e.g., 5:4). As the ratio increased, accuracy and stability were expected to decrease in accordance with the predicted frequency-locking dynamics of Fig. 1.

Each ratio was performed under three levels of visual occlusion: 0% (no occlusion), 50% (half of the visual information transmitted), and 90% (almost no visual information transmitted), corresponding to a within-subjects variable, %Occlusion. These %Occlusion levels resulted in reliable differences in performance of simple ratios during pilot testing. Intended Ratio and %Occlusion are manipulations of Ω and K, respectively.

Prior to the experiment, dyads were randomly assigned to either a 60 or 1000 ms goggle cycling rate corresponding to two levels of a between-subjects variable, Information

Update Rate. The 60 ms rate was identified during pilot testing as the rate at which participants reported being unable to identify onset/offset of goggle cycles, and the 1000 ms rate was identified as a rate at which participants reported that they could identify onset/offset of goggle occlusion cycles. Because vision was occluded per goggle cycle, %Occlusion was independent of Information Update Rate. That is, only the presentation rate changed for the Information Update Rate manipulation, and only the amount of information changed for the %Occlusion manipulation. For example, at 50%Occlusion, participants received exactly half of the visual information about each other's movements in both the 60 and 1000 ms Information Update Rate condition.

The purpose of having these two levels of Information Update Rate was to examine the human propensity to "fill-in" occluded information (Ramachandran and Gregory 1991) and experience apparent motion when the visual presentation is above a critical frame rate (Hochberg 1986) in the context of the hypothesized coupling dynamics. At the critical 60 ms rate (16.67 frames/s), images are "fused" together over occluded portions of the visual information stream (10 frames/s is the minimum requirement; Card et al. 1983), and the perception of motion between participants appears to be continuous. At the subcritical 1000 ms rate, however, subsequent images cannot be fused, and the perception of motion appears to be discontinuous with periods of motion interspersed with periods of no motion. If accuracy and stability are similar under both rates, then it means that coupling need not be continuous.

Based on power analyses from previous multifrequency experiments (Amazeen et al. 2001), we collected data from 10 dyads per between-subjects condition, and data collection continued until we had complete data records for all trials for 10 dyads in each between-subjects condition. Dyads completed 15 1-min randomized trials (i.e., Intended Ratio crossed with %Occlusion) at either the 60 or 1000 ms Information Update Rate. Hence, the experimental design was a 5 (Intended Ratio) $\times$ 3 (%Occlusion) $\times$ 2 (Information Update Rate) mixed factorial.

Procedure

Informed consent was obtained prior to participation. Participants were separated upon arrival for task training and preliminary measures. One participant received task training and performed a baseline trial, while the other participant completed a demographics questionnaire (not analyzed here). Participants then switched roles, such that each had received training, performed the baseline trial, and filled out the demographics questionnaire before participating as a dyad.

Training consisted of familiarizing each participant with the motion capture room, placement of the reflective markers, goggles, earbuds, and instructions regarding how to grip the PVC handlebar and oscillate their finger in the required manner. Participants were instructed to oscillate their finger while keeping it as straight as possible while keeping their finger pointed toward the opposite wall. The importance of attending to their partner's finger movements was emphasized by asking participants to briefly follow the experimenter's example (using a 3:1 finger movement pattern) to ensure that they understood the task; however, movements were not recorded at this time. Following training, the experimenter adjusted the handlebar and provided elbow padding if necessary.

Participants separately completed a baseline trial while wearing the marker ring, earbuds, and goggles. For the baseline trial, participants were instructed to simply oscillate their finger at a comfortable pace for 1 min. These data were collected for the purpose of identifying the naturally faster partner of the dyad. Based on these data, the naturally faster partner was assigned to be the "higher number" (faster oscillator), and the naturally slower partner was assigned to be the "smaller number" (slower oscillator) in all subsequent experimental trials. Based on pilot testing, this choice minimized fatigue and elicited a more natural pattern of frequency locking across dyads.

An experimenter informed dyads of the ratio to be performed before each trial and waited for confirmation from the dyad that they understood the intended ratio before initiating data collection. Dyads were also informed that "both the Low and High number person can adjust their speed to perform the ratio," but they could not talk to each other throughout the experiment. We chose to use this method because during pilot experiments, amount of occlusion did not reliably affect multifrequency stability when participants were externally paced using a metronome for the first 15sec of a trial and instructed to simply watch each other's movements when they could (i.e., an unintentional coordination manipulation; Fig. 3). We believe the problem with the unintentional manipulation was that when coordination became difficult (i.e., as amount of occlusion increases; at higher Farey tree levels), participants did not coordinate with each other through visual coupling but relied on the driving stimulus. Essentially, we think the metronome became a distinct driver of multifrequency performance that becomes confounded with the desired interpersonal coupling effects on multifrequency coordination (see also, Treffner and Turvey 1993). Therefore, we instructed participants to mutually adapt their movement frequencies to maintain an intended ratio (i.e., an intentional coordination manipulation), though we acknowledge this choice of eliciting interpersonal multifrequency performance may have
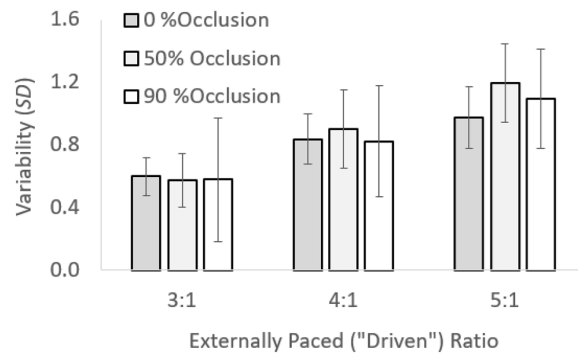
Fig. 3 Pilot data from Farey levels 2–4 showing the variability of multifrequency performance as a function of amount of visual occlusion using the externally paced multifrequency paradigm

elevated variability compared to standard multifrequency experiments that use a metronome.

All trials were initiated and terminated via an auditory beep that was delivered through the earbuds. The goggles were opaque prior to the start of a trial, strobed at the specified rate during the trial, and returned to opaque upon trial completion. Strobing cycles were identical for both members of the dyad. In all conditions, participants were instructed to keep their fingers in ready position (pointing at the opposite wall and parallel to the table) until the beep, at which time they began oscillating their fingers. The experimenter started and stopped trials remotely using a custom MATLAB (Mathworks, Inc.) script that synchronized data collection across motion capture, goggle cycles, and start/stop beeps. To minimize distraction, the dyads were the only people in the room during a trial. Following completion of the 15 experimental trials, participants were debriefed and dismissed. Participation lasted approximately 45 min.

Data and measures

Three-dimensional (*X, Y, Z*) movement data were streamed (100 Hz) into a computer using Vicon DataStream SDK 1.1.0 for MATLAB. Participants were instructed to oscillate their fingers along the transverse direction (*Z*-axis). The coordination of those vertical finger movement data was analyzed. Data for each trial were smoothed using a twenty-point running average to remove noise-like fluctuations that were faster than any intentional finger movement. Based on pilot studies, we removed the first and last 10 s of each 60-s trial to remove transient variation associated with the beginning and ending of each trial.

Following the precedent of Amazeen et al. (2001), we first calculated the movement frequency per cycle (peak-to-peak) for each member of the dyad and then

calculated frequency ratio by dividing the faster frequency by the slower frequency at the reference phase (peak) of the slower oscillator. The resulting frequency ratio time series was equal in length to the number of cycles for the slower oscillator. This approach for calculating frequency relations was deemed appropriate because it does not assume that the movement signals are stationary in time.

The proportion of turning points that occurred during un-occluded portions of the visual stream was measured for each dyad by calculating the number of movement peaks (i.e., the frequency-locking stimulus analyzed in this study) that occurred when the goggles were translucent divided by the total number of movement peaks in a trial. This measure was calculated separately for each partner and for the dyad. The results were similar using all three measures, and we report the dyad results in this paper.

Results

Preliminary analyses

Figure 4 depicts the smoothed time series of a representative dyad performing 1:1 and 3:1 in the 1000 ms Information Update Rate condition with 0%Occlusion. Not surprisingly, larger-integer ratios required longer cycle times, resulting in fewer cycles as the intended ratio Ω increased. Because dyads completed fewer cycles of larger-integer ratios (e.g., 3:1) compared to smaller-integer ratios (e.g., 1:1), proportion of cycles performed was used to standardize across this systematic discrepancy.

As expected, the baseline frequency of the faster partner ($M=1.27$ Hz, $S=0.42$) was significantly larger than the baseline frequency of the slower partner ($M=0.83$ Hz, $S=0.28$), $t(19)=5.80$, SE$=0.08$, $p<0.001$, $d=1.30$, and the frequencies of the slower and faster partner changed as a function of Ω: 1:1 ($M_{Fast} = 1.40$ Hz; $S_{Fast} = 0.55$; M_{Slow}

$= 1.44$ Hz; $S_{Slow} = 0.54$); 2:1 ($M_{Fast} = 1.80$ Hz; $S_{Fast} = 0.60$; $M_{Slow} = 0.95$ Hz; $S_{Slow} = 0.33$); 3:1 ($M_{Fast} = 2.24$ Hz; $S_{Fast} = 0.77$; $M_{Slow} = 0.94$ Hz; $S_{Slow} = 0.42$); 4:1 ($M_{Fast} = 2.59$ Hz; $S_{Fast} = 0.96$; $M_{Slow} = 0.91$ Hz; $S_{Slow} = 0.45$); and 5:1 ($M_{Fast} = 2.81$ Hz; $S_{Fast} = 1.00$; $M_{Slow} = 0.80$ Hz; $S_{Slow} = 0.41$). As instructed, partners mutually adjusted their movement frequencies to perform the intended ratio.

Because the faster partner's movements became more variable as the intended ratio increased, it raised the potential confound that only the faster partner's movements accounted for changes in overall ratio variability as the intended ratio Ω increased. To examine this possibility, we tested the correlation between overall ratio variability and the component variability of each partner measured at each trial in the experiment. Because there was no exact intended value for individual frequencies, standard deviations were the measure of variability (rather than relative absolute error) for these correlations. The correlations indicate that both the faster ($r(371)=0.56$, $p<0.001$) and slower ($r(371)=0.31$, $p<0.001$) participant variability drove overall variability and that the faster partner was only slightly more influential.

Data visualization

Although frequency locking was observed at both levels of Information Update Rate, the 1000 ms Information Update Rate led to results more consistent with model predictions, perhaps because the human visual system is more affected by coupling manipulations at that subcritical frame rate (see below). Therefore, we depict in Fig. 5 relative frequency distributions for each intended ratio at each level of the %Occlusion coupling parameter for the 1000 ms Information Update Rate condition.

Looking first at the 0%Occlusion condition in Fig. 5, notice how the preference for perfect mirroring (1:1) appears as a sharply peaked, unimodal distribution. As
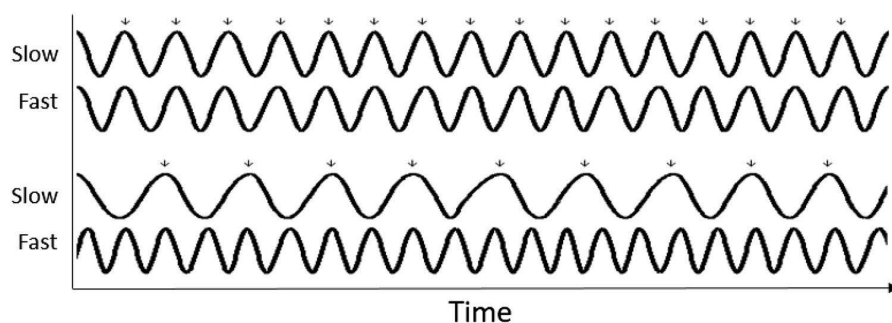
Fig. 4 Representative data from one dyad at the 1000 ms Information Update Rate with 0%Occlusion (Slow=slower partner; Fast=faster partner). *Arrows* indicate cycles performed by the slower member of the dyad for 1:1 (*top*) and 3:1 (*bottom*) intended ratios

over 10 s. Note that partners had to mutually adjust their movement frequencies (one speeding up and one slowing down) to perform the 3:1 ratio. As described in the text, performance of 3:1 trials tended to be less accurate and more variable than performance of 1:1 trials

Fig. 5 Relative frequency distributions of performed ratios by all dyads in the 1000 ms Information Update Rate condition as a function of Intended Ratio (Ω) and %Occlusion (K); *arrows* indicate the intended ratio
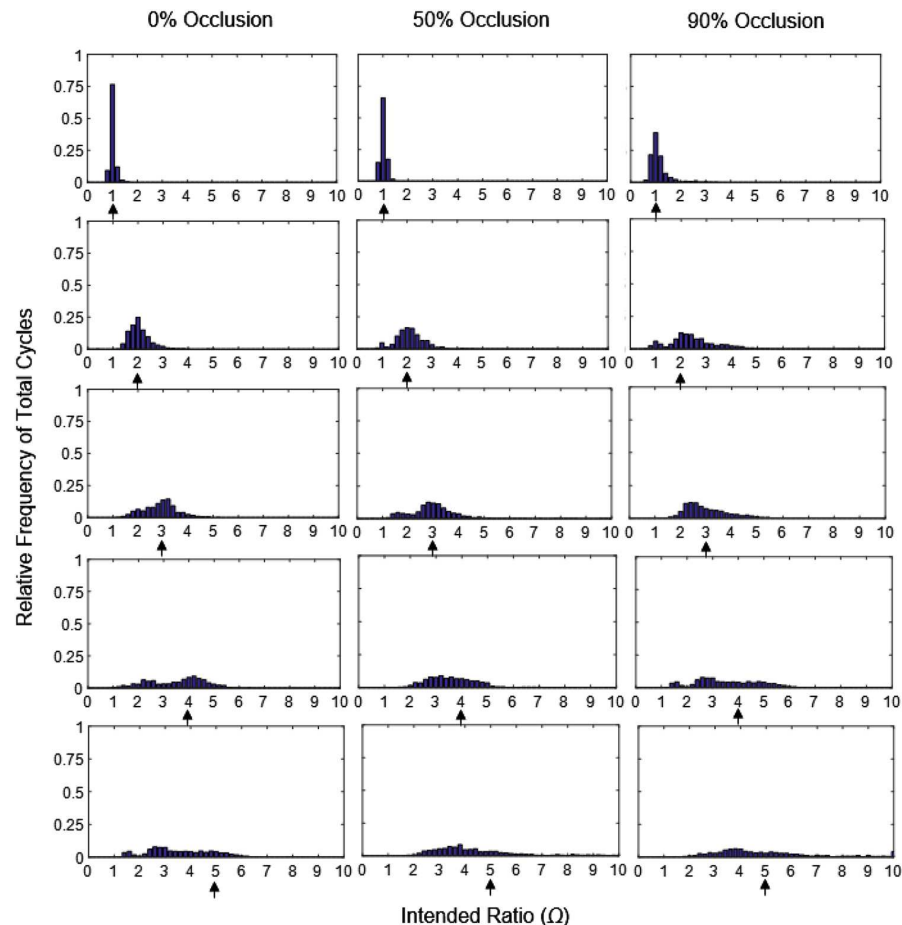
expected, the presence of peaks in the other panels indicates that dyads were able to perform other ratios (2:1, 3:1, 4:1, or 5:1), but a decrease in performance accuracy and stability was evident as a flattening of the distributions and, for the larger-integer ratios, the creation of a second peak. The same effect of %Occlusion is seen across all three columns: Flatter distributions were indicative of a decrease in performance stability with weaker coupling strength (i.e., greater %Occlusion).

As captured by the widths of the Arnold tongues and Farey tree levels in Fig. 1, larger-integer ratios should be less stable than smaller-integer ratios, which can be observed in Fig. 5 as the decay of the performance distributions along the vertical dimension of any column. Furthermore, as described by the varying widths of Arnold tongues, any tongue (any ratio) should become narrower (less stable) as coupling strength (K) decreases. This effect can be observed in Fig. 5 as the increasing spread (variability) along the horizontal dimension of any row.

Accuracy of multifrequency performance

More detailed evidence of how frequency-locking structures interpersonal performance can be seen in the proportion of cycles performed in the intended ratio, a measure of accuracy. The proportion of accurate cycles was calculated as the number of performed ratios within the tolerance windows of the Arnold tongues at $K=1$ identified by Treffner and Turvey (1993): $1/1 \pm 0.0714$ (Level 0); $1/2 \pm 0.0396$ (Level 1); $1/3 \pm 0.0172$ (Level 2); $1/4 \pm 0.0076$ (Level 3); and $1/5 \pm 0.0036$ (Level 4); relative to the number of all performed ratios that could be parsed at any level of the Farey tree. Because the Treffner and Turvey (1993) tolerance windows are taken from the Arnold tongues in the Ω interval [0, 1], we used fractional ratios for this analysis.

The two-frequency resonance model predicts that intended ratio (Ω) and coupling strength (K) parameters control ratio performance (Fig. 1a). Table 1 depicts those effects as systematic decreases moving left to right along

Table 1 Interval estimates (95%) of proportion of cycles performed in the intended ratio (intentional accuracy) as a function of visual information update rate and % visual occlusion

Visual coupling manipulations		Intended ratio (Ω)				
Update rate	%Occlusion (K)	1:1	2:1	3:1	4:1	5:1
60 ms	0	0.99 (±0.01)	0.65 (±0.20)	0.38 (±0.16)	0.23 (±0.17)	0.17 (±0.17)
60 ms	50	0.98 (±0.03)	0.53 (±0.24)	0.52 (±0.17)	0.51 (±0.26)	0.23 (±0.15)
60 ms	90	0.99 (±0.01)	0.56 (±0.16)	0.36 (±0.16)	0.18 (±0.15)	0.28 (±0.24)
1000 ms	0	0.99 (±0.02)	0.61 (±0.16)	0.59 (±0.18)	0.44 (±0.23)	0.36 (±0.24)
1000 ms	50	0.98 (±0.02)	0.55 (±0.20)	0.50 (±0.19)	0.13 (±0.11)	0.13 (±0.13)
1000 ms	90	0.85 (±0.19)	0.36 (±0.21)	0.33 (±0.11)	0.22 (±0.18)	0.17 (±0.20)

any row (as Ω moves further from 1:1) and moving down any column (as K decreases).

To assess the effects of our coupling strength and intended ratio manipulations, we conducted a 5 (Intended Ratio) × 3 (%Occlusion) × 2 (Information Update Rate) mixed ANOVA on the accuracy scores. The main effect of Information Update Rate was not significant ($p = 0.70$), indicating that, overall, accuracy was similar across the 60 ms and 1000 ms update rates. The three-way interaction was significant, $F (8, 144) = 2.58$, MSE $= 0.04$, $p = 0.012$, $\eta_p^2 = 0.13$, however. The simple Intended Ratio × %Occlusion interaction was significant for the 60 ms Information Update Rate condition, $F (8, 144) = 2.17$, MSE $= 0.04$, $p = 0.033$, $\eta_p^2 = 0.10$, but not for the 1000 ms Information Update Rate condition ($p = 0.23$). This suggests that Ω (intended ratio) and K (visual coupling) independently controlled multifrequency performance in the 1000 ms condition only (Table 1).

Figure 6a illustrates the main effect of Intended Ratio on accuracy, $F (4, 72) = 55.12$, MSE $= 0.09$, $p < 0.001$, $\eta_p^2 = 0.75$. In support of model predictions, significant decreases in accuracy scaled inversely with Farey level as the intended ratio changed from 1:1 to 5:1. Although the accuracy decrease moving from 4:1 to 5:1 was not statistically significant, the accuracy decrease two Farey levels apart, from 3:1 to 5:1, was significant.

The main effect of %Occlusion was significant, $F (2, 36) = 5.15$, MSE $= 0.06$, $p = 0.011$, $\eta_p^2 = 0.22$; accuracy decreased as %Occlusion increased. However, Fig. 6b illustrates the interaction between %Occlusion and Information Update Rate, $F (2, 36) = 5.50$, MSE $= 0.06$ $p = 0.008$, $\eta_p^2 = 0.23$. The expected pattern of decreasing accuracy as visual coupling decreased was evident in the 1000 ms Information Update Rate but not in the 60 ms Information Update Rate condition. If the visual information update rate is fast enough (i.e., beyond the critical fusion frame rate > 10 frames/s; Card et al. 1986), then it is easier for dyads to follow movements over occluded portions of the visual stream in order to accurately perform the intended ratio.
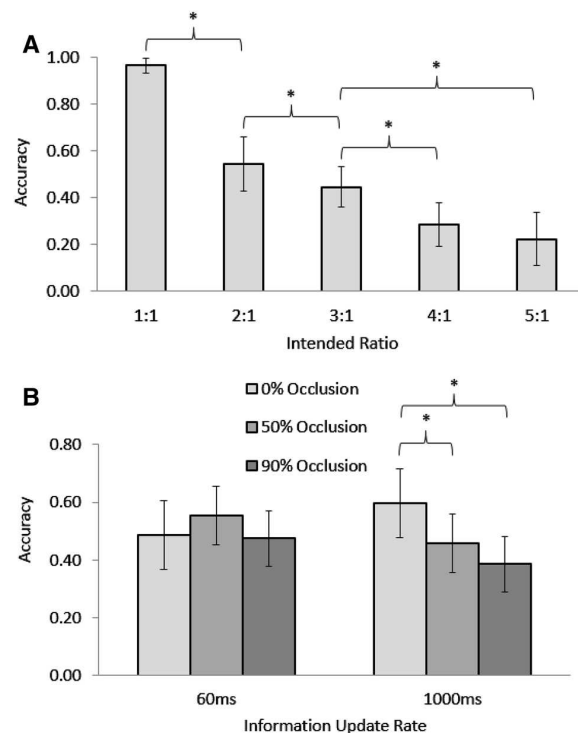
Fig. 6 a Proportion of cycles performed in the intended ratio (accuracy) as a function of intended ratio (Ω) and **b** the effect of %Occlusion (coupling strength; K) on Accuracy depended on Information Update Rate (*error bars* are 95% confidence intervals; *$p < 0.05$)

Variability (instability) of multifrequency performance

As Ω increased and K decreased, frequency distributions flattened around the intended ratio (Fig. 5). To capture that increasing variability (decrease in performance stability), we averaged the relative absolute error (RAE) of frequency ratios across all cycles in each trial (Table 2). We used RAE as the measure of variability rather than standard deviation because its calculation does not directly depend on sample size, which systematically

Table 2 Interval estimates (95%) of the relative absolute error (variability) of all frequency ratios for each intended ratio as a function of visual information update rate and % visual occlusion

Visual coupling parameters		Intended ratio (Ω)				
Update rate	%Occlusion (K)	1:1	2:1	3:1	4:1	5:1
60 ms	0	0.07 ($\pm$0.02)	0.15 ($\pm$0.05)	0.22 ($\pm$0.07)	0.23 ($\pm$0.08)	0.26 ($\pm$0.11)
60 ms	50	0.07 ($\pm$0.02)	0.19 ($\pm$0.08)	0.20 ($\pm$0.10)	0.20 ($\pm$0.06)	0.20 ($\pm$0.09)
60 ms	90	0.08 ($\pm$0.07)	0.19 ($\pm$0.09)	0.24 ($\pm$0.07)	0.25 ($\pm$0.09)	0.26 ($\pm$0.11)
1000 ms	0	0.07 ($\pm$0.02)	0.14 ($\pm$0.05)	0.15 ($\pm$0.07)	0.22 ($\pm$0.08)	0.27 ($\pm$0.11)
1000 ms	50	0.07 ($\pm$0.02)	0.20 ($\pm$0.08)	0.21 ($\pm$0.10)	0.26 ($\pm$0.06)	0.28 ($\pm$0.09)
1000 ms	90	0.20 ($\pm$0.07)	0.33 ($\pm$0.09)	0.21 ($\pm$0.07)	0.26 ($\pm$0.09)	0.34 ($\pm$0.11)

increased as the intended ratio became smaller. In support of model predictions, variability tended to increase as Intended Ratio deviated further from perfect mirroring. This can be seen as increasing variability moving left to right across the rows (as Ω moves further from 1:1) in Table 2. Patterns of variability moving down the columns suggest that decreasing K (increasing %Occlusion) tends to make ratios less stable, which is also consistent with model predictions.

To assess the effects of our coupling strength and intended ratio manipulations, we conducted a 5 (Intended Ratio)×3 (%Occlusion)×2 (Information Update Rate) mixed ANOVA on the variability scores. The main effect of Information Update Rate was not significant ($p = 0.36$), indicating that, overall, variability was similar across the 60 and 1000 ms update rates. Although the pattern of variability for the 1000 ms Information Update Rate condition appears to be more consistent with model predictions than the 60 ms condition (Table 2), there was no significant Intended Ratio × %Occlusion × Information Update Rate interaction ($p = 0.40$).

The main effect of Intended Ratio was significant, $F_{(4, 72)} = 13.95$, $MSE = 0.02$, $p < 0.001$, $\eta_p^2 = 0.44$. As shown in Fig. 7a, the pattern of mean variability scores increased as ratio increased in support of model predictions. However, variability for 2:1 was unexpectedly large relative to the other intended ratios (see Table 2, 1000 ms 2:1 with 90%Occlusion), and, unlike Accuracy, all statistically significant increases occurred two Farey levels apart (i.e., 1:1 versus 3:1 and 3:1 versus 5:1).

The main effect of %Occlusion was significant, $F_{(2, 36)} = 13.41$, MSE = 0.01, $p < 0.001$, $\eta_p^2 = 0.43$; variability increased as %Occlusion increased. However, Fig. 7b illustrates the significant interaction between %Occlusion and Information Update Rate, $F_{(2, 36)} = 5.22$, $MSE = 0.01$ $p = 0.01$, $\eta_p^2 = 0.23$. As with accuracy, the predicted pattern of increasing variability as visual coupling decreased was evident for the 1000 ms Information Update Rate but not for the 60 ms Information Update
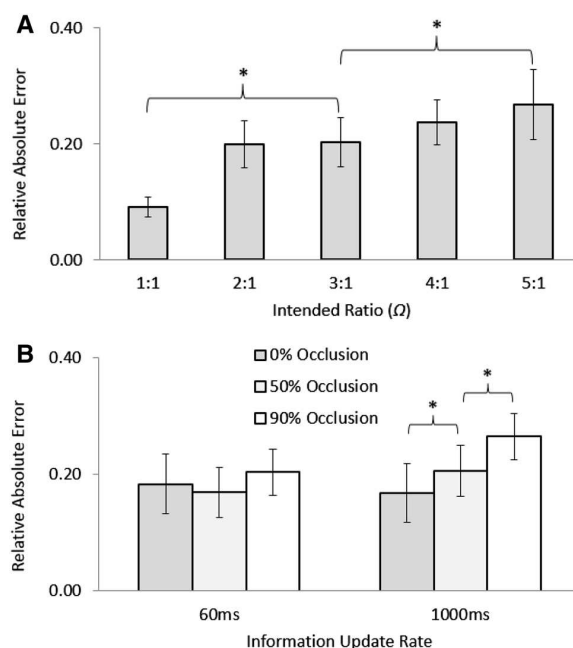
Fig. 7 **a** Relative absolute error of performed frequency ratios (Instability) as a function of intended ratio (Ω) and **b** the effect of %Occlusion (coupling strength; K) on Instability depended on Information Update Rate (*error bars* are 95% confidence intervals; *$p < 0.05$)

Rate condition. Like accuracy, if the visual information update rate is fast enough, then it is easier for dyads to maintain performance stability over occluded portions of the visual stream.

In agreement with the accuracy results, results for the 1000 ms Information Update Rate condition appeared to be more consistent with model predictions (Table 2). As with accuracy, we think that the propensity of the visual system to fill in occluded information when it can may account for discrepancies with model predictions in the 60 ms Information Update Rate condition.

Turning points

To assess whether the proportion of turning points that occurred during un-occluded vision accounted for the observed differences in pattern stability, we conducted a 5 (Intended Ratio) × 2 (%Occlusion) × 2 (Information Update Rate) mixed ANOVA on the proportion of un-occluded turning points in dyads. Because there was no visual occlusion in the 0%Occlusion condition, only the 50 and 90%Occlusion conditions were analyzed. Only the %Occlusion main effect was significant, F (1, 36) = 1396.49, MSE = 0.01, $p < 0.001$, $\eta_p^2 = 0.99$. This is due to the fact that half of the turning points in the 50% condition ($M = 0.51$; SE = 0.01), and one-tenth of the turning points in the 90% condition ($M = 0.10$; SE = 0.01) occurred when vision was un-occluded. However, these proportions correspond to what would be expected to occur by chance when 50 and 90% of visual information is occluded, respectively. Dyads did not stabilize multifrequency performance by adjusting their turning points.

Discussion

These results demonstrate how frequency locking accounts for changes in interpersonal coordination processes across pattern variation. The model accounted not only for the preference of 1:1 frequency locking (mirroring) that is commonly displayed in the psychological literature but correctly predicted performance across a range of simple multifrequency ratios beyond 1:1. In this light, interpersonal multifrequency coordination appears to abide by the same dynamical principles underlying intrapersonal coordination in drumming (Peper et al. 1995), motor-respiratory coordination (Hessler and Amazeen 2014), and spontaneous visual-motor coordination (Washburn et al. 2014). Apparently, social coordination involves not just the intention to coordinate but dynamical constraints on frequency locking, just as do other multifrequency phenomena in the physical, biological, and chemical world.

In accordance with model predictions for the intended ratio Ω, performance of smaller-integer ratios (1:1; 2:1; 3:1) was both more accurate and stable than was performance of larger-integer ratios (4:1; 5:1). This result is unsurprising and simply demonstrates that the challenge of coordinating with another individual increases with increasing frequency differences. Studies are underway to test complex ratios (e.g., 3:2; 7:5) in which frequency differences are not as straightforward (Gibbons et al. 2015). A significant finding was that the amount of visual information exchange scaled to coupling strength (K). Regardless of the ratio, performance improvements were observed as a function of increases in mutual visual

information. This supports the predictions of the Arnold tongues (Fig. 1a), such that increasing the amount of coupling for any ratio (Ω) had the effect of widening its tongue. This conforms with findings across physiological subsystems of the body (e.g., motor-respiratory coordination, Amazeen et al. 2001; Hessler and Amazeen 2014; Hessler et al. 2010) and within motor subsystems of the body (Peper et al. 1995; Treffner and Turvey 1993), as well as the role of vision in unintentional and intentional 1:1 synchronization between people (Ouiller et al. 2008; Richardson et al. 2007). However, this study helps expand the coupled oscillator theory of human coordination by accounting for incompatible, non-mirroring rhythms between people.

As the difficulty of the intended ratio (i.e., Farey level) increased, both accuracy and stability suffered in spite of the slower participant becoming slower and the faster participant becoming faster (i.e., "trading off" speeds), which presumably simplified the coordination task. To our knowledge, the predictions of the two-frequency resonance model do not assume that any of the constituent frequencies remain fixed, only that the ratio of the two frequencies approximates the intended ratio. Given that the results were largely consistent with model predictions, we think that trading off speeds might present an optimal ("self-organized") solution for interpersonal multifrequency coordination in the current study, but that overall, the limits on interpersonal performance were governed by frequency locking.

Research on 1:1 coordination indicates that turning points of an oscillatory stimulus may provide privileged visual information for synchronization to occur. More specifically, research suggests that turning points, and not amount of visual information, are the relevant visual information for intentional rhythmic coordination (Hajnal et al. 2009). In the present study, turning points played no role beyond chance levels in stabilizing intentional interpersonal multifrequency coordination, although amount of visual information was directly related to both accuracy and stability of coordination. This is consistent with the finding that unintentional synchronization depends on amount of information picked up rather than turning points (Varlet et al. 2015). We think that when synchronization becomes more complex than 1:1 (e.g., 2:1; 3:1; etc.), turning points may not be reliable sources of information for interpersonal coupling. The present study is limited, however, in that we did not control visual occlusion by manipulating the phase of movement that is occluded. Future research should attempt to determine whether higher-order informational variables for interpersonal multifrequency coordination exist by selectively occluding portions of partners' movements when those movements differ in frequency (i.e., "relative" turning points).

When visually coupled individuals intentionally perform a pattern, the information exchange depends on the visual system. Therefore, it is important to understand how multifrequency performance is constrained both by frequency locking and inherent characteristics of the visual system. This is demonstrated in the current study as the moderating effect of rate of visual information presentation on frequency locking. The finding that visual coupling effects were more pronounced when presented at a subcritical frame rate (1000 ms) versus a critical rate (60 ms) implies that humans do, to some degree, fill in missing aspects of visual information as the signal degrades to preserve performance. This is not anticipated by the dynamical model but demonstrates how the inherent characteristics of human information processing blend with dynamical constraints to produce novel behavior patterns across coordinating individuals.

We can see how these ideas start to generalize by observing how actual teams develop coordinated solutions to novel coordination problems. In collaboration with the National Double Dutch League, we have conducted field research to observe multifrequency performance in the sport of Double Dutch (Fig. 8). As we would expect, a 1:1 foot-to-rope ratio (mirroring) is the simplest (even for beginners); however, a highly practiced Double Dutch team (Fig. 8a) can reliably produce even the most unstable

Fig. 8 **a** An experienced Double Dutch team; **b** performance of a 7:5 (foot:rope) multifrequency ratio by the experienced Double Dutch team
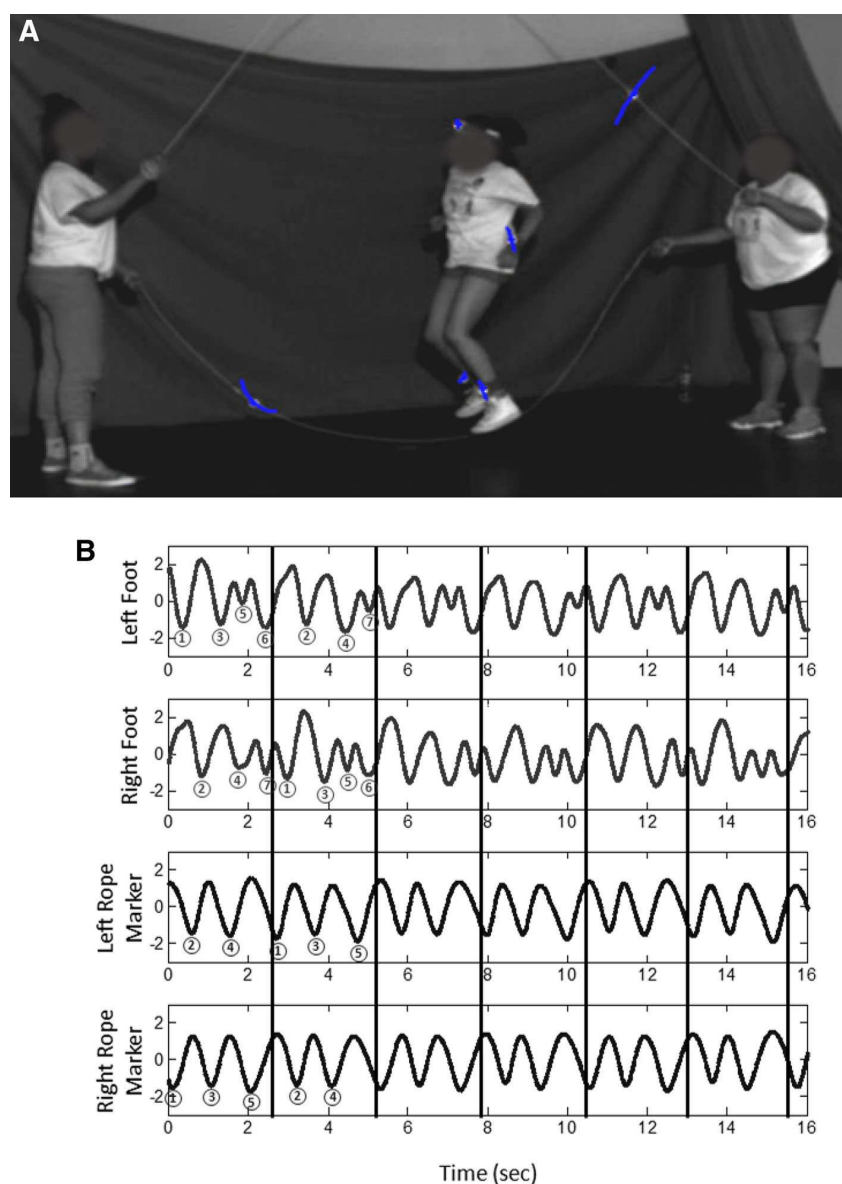
of ratios. Depicted in Fig. 8b, the jumper produces seven footfalls for every five rope turns: a 7:5 frequency ratio. Several cycles of this pattern are depicted, and this pattern was remarkably consistent, given the difficulty predicted by the two-frequency resonance model. How do Double Dutch teams stabilize this pattern, and how is it related to what we observe in the laboratory?

In one study, participants from the 2014 National Double Dutch League summer camp were recruited to intentionally perform both simple and complex movement ratios (foot falls:rope turn) in a self-paced, intentional manner, similar to the experiment reported in this paper. Their movements were recorded on video and later digitized with reference to the markers shown in Fig. 8a.

Just as the skilled shoe-tier, drummer, or musician must learn to move the hands independently to break the spontaneous mirroring tendency, experienced Double Dutch teams adjust their patterns by breaking up and modifying their pattern cycle-by-cycle (Fig. 8b). We have observed that as they move further from the 1:1 perfect mirroring pattern, both the jumper and turners mutually adjust their movement frequency by more closely watching each other's movements and counting their rhythm out loud. In other words, they amplify their most salient forms of coupling to facilitate performance. The use of multiple forms of coupling—visual, haptic, acoustic—is consistent with what we observe in the laboratory when we allow participants to use visual information about each other's movements to control their coordination pattern. Hence, our field observations conform to our laboratory findings suggesting that informational coupling becomes increasingly important as people explore coordination patterns that deviate from mirroring.

Conclusion

Although there is an overwhelming tendency in both living and nonliving systems to define synchronization as perfect mirroring, because it is observed so often, most tasks people perform both alone and in teams require a break from mirroring towards other forms of synchronization. Defined as 1:1 frequency-locked coordination, perfect mirroring and its relative, reflectional mirroring, form only a tiny subset of possible frequency ratios whose performance is captured by the parameters of a two-frequency resonance model. In this study, the intentional performance of simple interpersonal rhythms (e.g., 2:1; 3:1) was shown to be constrained both by frequency locking and natural characteristics of the human visual system. The relatively simple dynamical principle of frequency locking coupled with inherent properties of human perceptual systems could provide a parsimonious model of multifrequency performance in rhythmic human activities such as dancing and sports.

However, more complex rhythms (e.g., 3:2; 4:3) are more difficult for individuals to perform (Treffner and Turvey 1993), and it remains to be seen how dyads and teams perform these more complex rhythms both intentionally and unintentionally.

There is a tendency in psychology to focus on neural and cognitive processes within the individual to explain interpersonal behavior. However, this study demonstrates the role that relational parameters and dynamics play in the formation of novel interpersonal patterns. We think that interpersonal behavior is defined not just by social, perceptual, and cognitive mechanisms within the individual but by general coordination principles that govern our interactions with each other and the world (Cooke et al. 2013; Gorman 2014). In this light, the question of how dynamic relations such as synchronization come to structure thought and action may be one that is inherently interactive and relational in origin.

References

Albert NB, Ivry RB (2009) The persistence of spatial interference after extended training in a bimanual drawing task. Cortex 45:377–385

Amazeen PG (2002) Is dynamics the content of a generalized motor program for rhythmic interlimb coordination? J Mot Behav 34:233–251

Amazeen PG, Schmidt RC, Turvey MT (1995) Frequency detuning of the phase entrainment dynamics of visually coupled rhythmic movements. Biol Cybern 72:511–518

Amazeen PG, Amazeen EL, Turvey MT (1998) Dynamics of human intersegmental coordination: Theory and research. In: Rosenbaum DA, Collyer CE (eds) Timing of behavior: Neural, computational, and psychological perspectives. MIT, Cambridge, pp 237–259

Amazeen PG, Amazeen EL, Beek PL (2001) Coupling of breathing and movement during manual wheelchair propulsion. J Exp Psychol Hum Percept Perform 27:1243–1259

Bak P (1986) The devil's staircase. Phys Today 39:38–45

Card S, Moran TP, Newell A (1983) The psychology of human computer interaction. Lawrence Erlbaum Associates, Mahwah

Chartrand TL, Bargh JA (1999) The chameleon effect: The perception-behavior link and social interaction. J Pers Soc Psychol 76:893–910

Cooke NJ, Gorman JC, Myers CW, Duran JL (2013) Interactive team cognition. Cognitive Science 37:255–285

deGuzman GC, Kelso JAS (1991) Multifrequency behavioral patterns and the phase attractive circle map. Biol Cybern 64:485–495

Fontaine RJ, Lee TD, Swinnen SP (1997) Learning a new bimanual coordination pattern: Reciprocal influences of intrinsic and to-be-learned patterns. Can J Exp Psychol 51:1–9

Gibbons CT, Likens AD, Amazeen PG (2015) Multifrequency coordination in dyads. In: Weast-Knapp J, Malone M, Abney D (eds) Studies in perception & action XIII. Taylor & Francis Group, LLC, New York, NY

Gipson CL, Gorman JC, Hessler ER (2016) Top-down (prior knowledge) and bottom-up (perceptual modality) influences on spontaneous interpersonal coordination. Nonlinear Dynam Psychol Life Sci 20:193–222

Glazier JA, Libchaber A (1988) Quasi-periodicity and dynamical systems. IEEE Trans Circ Syst 35:790–809

Gonzales LM, Hessler EE, Amazeen PG (2010) Perceptual constraints on frequency ratio performance in motor-respiratory coordination. Ecol Psychol 22:1–24

Gorman JC (2014) Team coordination and dynamics: two central issues. Curr Direct Psychol Sci 23:355–360

Gorman JC, Crites MJ (2015) Learning to tie well with others: Bimanual versus intermanual performance of a highly practised skill. Ergonomics 58:680–697

Hajnal A, Richardson MJ, Harrison SJ, Schmidt RC (2009) Location but not amount of stimulus occlusion influences the stability of visuo-motor coordination. Exp Brain Res 199:89–93

Hessler EE, Amazeen PG (2014) Learning and transfer in motor-respiratory coordination. Hum Mov Sci 33:321–342

Hessler EE, Gonzales LM, Amazeen PG (2010) Displays that facilitate performance of multifrequency ratios during motor-respiratory coordination. Acta Psychol 133:96–105

Hochberg J (1986) Representation of motion and space in video and cinematic displays. In: Boff KR, Kaufmann L, Thomas JP (eds) Handbook of perception and human performance. Wiley, New York, pp 22–1-22-64

Kelso JAS (1984) Phase transitions and critical behavior in human bimanual coordination. Am J Physiol 246:R1000–R1004

Kelso JAS (1995) Dynamic patterns: the self-organization of brain and behavior. MIT, Cambridge

Lee TD, Swinnen SP, Verschueren S (1995) Relative phase alterations during bimanual skill acquisition. J Mot Behav 27:263–274

Mechsner F, Kerzel D, Knoblich G, Prinz W (2001) Perceptual basis of bimanual coordination. Nature 414:69–73

Ouiller O, de Guzman GC, Jantzen KJ, Lagarde J, Kelso JAS (2008) Social coordination dynamics: measuring human bonding. Soc Neurosci 3:178–192

Peper CE, Beek PJ, van Wieringen PCW (1995) Multifrequency coordination in bimanual tapping: Asymmetrical coupling and signs of supercriticality. J Exp Psychol Hum Percept Perform 21:1117–1138

Pikovsky A, Rosenblum M, Kurths J (2001) Synchronization: A universal concept in nonlinear science. Cambridge University Press, Cambridge

Ramachandran VS, Gregory RL (1991) Perceptual filling in of artificially induced scotomas in human vision. Nature 350:699–702

Richardson MJ, Marsh KL, Isenhower RW, Goodman JRL, Schmidt RC (2007) Rocking together: dynamics of intentional and unintentional interpersonal coordination. Hum Mov Sci 26:867–891

Schmidt RC, Carello C, Turvey MT (1990) Phase transitions and critical fluctuations in the visual coordination of rhythmic movements between people. J Exp Psychol Hum Percept Perform 16:227–247

Strogatz S (2003) Sync: the emerging science of spontaneous order. Hyperion, New York

Swinnen SP, Lee TD, Verschueren S, Serrien J, Bogaerds H (1997) Interlimb coordination: Learning and transfer under different feedback conditions. Hum Mov Sci 16:749–785

Treffner PJ, Turvey MT (1993) Resonance constraints on rhythmic movement. J Exp Psychol Hum Percept Perform 19:1221–1237

Tuller B, Kelso, J. A. S. (1989) Environmentally-specified patterns of movement coordination in normal and split-brain subjects. Exp Brain Res 75:306–316

Varlet M, Richardson MJ (2015) What would be Usain Bolt's 100-meter sprint world record without Tyson Gay? J Exp Psychol Hum Percept Perform 41:36–41

Varlet M, Bucci C, Richardson MJ, Schmidt RC (2015) Informational constraints on spontaneous visuomotor entrainment. Hum Mov Sci 41:265–281

Washburn A, Coey CA, Romero V, Richardson MJ (2014) Visual multifrequency entrainment: Can 1:2, 2:3, and 3:4 coordination occur spontaneously? J Mot Behav 46:247–257

Yamanishi J, Kawato M, Suzuki R (1980) Two coupled oscillators as a model for the coordinated finger tapping by both hands. Biol Cybern 37:219–225

Zanone PG, Kelso JAS (1992a) Evolution of behavioral attractors with learning: Nonequilibrium phase transitions. J Exp Psychol Hum Percept Perform 18:403–421

Zanone PG, Kelso, JAS (1992b) Learning and transfer as dynamical paradigms for behavioral changes. In: Stelmach GE, Requin J (eds) Tutorials in motor behavior: II. North-Holland, Amsterdam, pp 563–582

Zanone PG, Kelso JAS (1997) Coordination dynamics of learning and transfer: Collective and component levels. J Exp Psychol Hum Percept Perform 23:1454–1480