Exp Brain Res
DOI 10.1007/s00221-010-2388-y

RESEARCH ARTICLE

Learning a coordinated rhythmic movement with task-appropriate coordination feedback

Andrew D. Wilson · Winona Snapp-Childs · Rachel Coats · Geoffrey P. Bingham

Received: 30 April 2010 / Accepted: 28 July 2010

Abstract A common perception–action learning task is to teach participants to produce a novel coordinated rhythmic movement, e.g. 90° mean relative phase. As a general rule, people cannot produce these novel movements stably without training. This is because they are extremely poor at discriminating the perceptual information required to coordinate and control the movement, which means people require additional (*augmented*) feedback to learn the novel task. Extant methods (e.g. visual metronomes, Lissajous figures) work, but all involve transforming the perceptual information about the task and thus altering the perception–action task dynamic being studied. We describe and test a new method for providing online augmented *coordination feedback* using a neutral colour cue. This does not alter the perceptual information or the overall task dynamic, and an experiment confirms that (a) feedback is required for learning a novel coordination and (b) the new feedback method provides the necessary assistance. This task-appropriate augmented feedback therefore allows us to study the process of learning while preserving the perceptual information that constitutes a key part of the task dynamic being studied. This method is inspired by and supports a fully perception–action approach to coordinated rhythmic movement.

Keywords Perception–action · Coordinated rhythmic movement · Augmented feedback · Learning

A. D. Wilson (✉)
Centre for Sport and Exercise Sciences, Institute of Membrane and Systems Biology, University of Leeds, Leeds LS2 9JT, UK
e-mail: A.D.Wilson@leeds.ac.uk

W. Snapp-Childs · R. Coats · G. P. Bingham
Department of Psychological and Brain Sciences, Indiana University, Bloomington, IN, USA

Introduction

A key model task for studying human movement is *coordinated rhythmic movement*, first described by Kelso (1981). The task is simply to coordinate rhythmic movements (of limbs, or pendulums, or stimuli on a computer screen) at some mean relative phase. In general, people can only produce two stable coordination patterns without training, specifically 0° and 180°. Other patterns (e.g. 90°) can, but must, be learned (see Kelso 1995 for a useful overview).

These characteristic phenomena have been described from a *dynamic pattern perspective*. Behaviour is said to be organized with respect to the order parameter relative phase; 0° and 180° are attractors in this space and are described in terms of homologous muscle activation (Haken et al. 1985; Kelso 1995). Learning a novel coordinated movement entailed the creation of a new attractor at the target relative phase, in competition with the two intrinsic states (Zanone and Kelso 1994). From this perspective, the specifics of the feedback display are not critical, so long as it supports the acquisition of stable movement; stability is the organizing principle (Tallet et al. 2008). However, there is now extensive evidence that the coupling entailed by coordination is *perceptual* and that behaviour is actually organized with respect to the *information* for relative phase[1]:

1. The phenomena persist when the coordination is performed between people (e.g. Schmidt et al. 1990;

[1] The stability of any specific coordinated movement is determined by multiple constraints (e.g. muscle homology; Li et al. 2004), but the underlying structure (as described by the HKB model; Haken et al. 1985) comes from the *coordination* requirement, which necessarily entails perception.

Published online: 12 August 2010

Temprado et al. 2003) and between people and a display (Buekers et al. 2000; Wilson et al. 2005a; Wimmers et al. 1992; Hajnal et al. 2009).
2. The phenomena persist for perceptual judgements, both visual (Bingham et al. 1999; Bingham et al. 2000; Zaal et al. 2000; Bingham 2004a) and proprioceptive (Wilson et al. 2003).
3. Learning is easier, not harder and close to the stable states; rather than serving as competition for resources (Zanone and Kelso 1994), the regions around 0° and 180° are perceptually discriminable (Wenderoth et al. 2002; see also Fontaine et al. 1997; Tallet et al. 2008, 2010).

These data have led to the development of a *perception–action perspective*, which proposes that the phenomena emerge from a task dynamic that includes perceptual information as a crucial element. Bingham (2001, 2004a, b) has modelled this dynamic, and phase is predicted to be perceived as the relative direction of motion of the oscillators, the detection of which is modified by their relative speed. Relative direction has long been implicated as a crucial component to the basic task dynamic (Bogaerts et al. 2003; Wilson et al. 2005b), and recent psychophysical evidence has supported the hypothesis more directly (Wilson and Bingham 2008).

Learning

Learning to produce initially unstable movements (e.g. 90°) requires *augmented feedback* (information above and beyond the *inherent feedback* contained in the task; Schmidt and Lee 1999), because inherent feedback about performance in this task is not often perceptually accessible. Bingham and colleagues have exhaustively documented the fact that perceptual judgments of coordinated rhythmic movements other than 0° and 180° are highly variable, with 90° maximally so. In addition, people cannot discriminate added levels of phase variability at 90°, because it is already judged to be maximally variable. This pattern is true of both visual (Bingham et al. 1999, 2000; Zaal et al. 2000) and proprioceptive (Wilson et al. 2003) judgments and is readily explained if relative phase is perceived prior to learning as relative direction. Relative direction is maximally variable at 90°, and variable information cannot support stable action. This fact predicts that learning 90° will actually entail learning to use different information, and this is indeed the case (Wilson and Bingham 2008).

The practical upshot of these results for trying to learn to produce movements at 90° is that even if a person is actually moving at 90°, they will not be able to detect that they are successful and when they inevitably begin to drift away from 90°, they will not detect the increased variability in their movements until it is too late to make a timely correction. Learning requires a clear goal and a way to assess performance relative to that goal, neither of which is possible here without help from a feedback display.

Augmented feedback methods for training coordinated rhythmic movements are *visual metronomes* and *Lissajous figures.* However, as described below, both of these methods actually transform the task so that it is no longer a coordination task; this makes them of limited use for exploring the specific task dynamic described from the perception–action perspective (i.e. the model in Bingham 2001, 2004a, b). The goal of the current experiment is to therefore develop and test a new method of feedback, *coordination feedback*, which is suitable for our purposes.

Current feedback methods

Visual metronomes

Zanone and Kelso (1992a, b, 1997) and Tallet et al. (2008, 2010) have trained participants to move at either 45°, 90° or 135° using a visual metronome. This setup entails two lights, one for each limb to be moved; the two lights alternate with timing that specifies a required mean relative phase. This method, however, alters the task from one coordinated rhythmic movement to two separate tracking tasks, and Rosenbaum et al. (2006) have demonstrated that people can readily track two non-identical movements to produce coordinated movements they would not otherwise be able to maintain. Wilson et al. (2003) explicitly took advantage of this fact and had participants haptically track two manipulanda in order to produce movements at 90°. Participants were able to move at 90° by tracking the devices, but this did not provide any readily detectable information that could serve as the basis for learning. Tracking and coordination are not the same task.

Lissajous figures

Lissajous figures are a visual representation of relative motion information (the result of plotting the position of the things being coordinated against each other). Participants are asked to move so as to make a real-time plot of their movements' line up with a reference shape (e.g. a circle for 90°). This has been used with great success in numerous studies (e.g. Debaere et al. 2004; Lee et al. 1995; Maslovat et al. 2009; Temprado and Swinnen 2005; Wenderoth and Bock 2001; Wenderoth et al. 2002).

Lissajous figures are *transformed visual feedback*; instead of displaying multiple targets which must be coordinated, they use a single target that represents the motion of the two limbs, which must be controlled to match a template shape. Transforming the feedback to remove the coordination aspect is known to alter the task dynamics. Kovacs et al. (2009) established that participants can readily produce a wide range of normally unstable coordinated movements using this feedback with little training. Changing the display makes the required information detectable, which in turn makes the required movement possible. This is similar to findings by Wilson et al. (2005a), who demonstrated that participants could produce movements at 90° without training if the mapping between the movement and the display was altered so that moving at 90° produced a display showing 0° (see also Bogaerts et al. 2003, who stabilized non-0° movements with transformed visual displays). Altering the display changes the task dynamic.

The task dynamic

Both current methods of augmented feedback entail that the perceptual information for this task, relative direction, is not defined in the feedback display. This in turn will alter the process of acquiring a novel coordination; the task is now different. If one is interested in the process of learning or the role of perceptual information, as we are, then it is imperative that the training and assessment sessions take place under the same 'rules', i.e. the same task dynamic. Two recent studies from our laboratory support this. Wilson et al. (2010) trained participants to be expert perceivers of 90°. This perceptual expertise translated directly into improved movement stability without any practice at the movement task; stable perception led to stable action, because the perceptual training task contained the same information as required for the action task. Wilson and Bingham (2008) then established that learning to perceive 90° entails learning to use a new information variable (relative position: 90° is specified by the temporal alignment of the peak speed of one oscillator with the peak amplitude of the other). This result also accounts for a common result, whereby learning at 90° only generalizes to 270° (e.g. Zanone and Kelso 1997)—the consequences of learning follow the information. The implication was that in a 'full cue' coordinated rhythmic movement task, relative position information is (a) available and (b) suitably stable at 90° to be worth learning. This will (artificially) not be the case under conditions of transformed feedback methods.

The goal of the current research was therefore to develop and test a method of providing augmented feedback that could drive learning but not alter the informational content of the task. Our solution (see Appendix: coordination feedback) is to toggle the colour of the target that participants control with a joystick when they are at the target relative phase, plus or minus some error bandwidth. Colour is a useful parameter, for both theoretical and empirical reasons. First, Bingham's model (Bingham 2001, 2004a, b) assumes that the relevant information is related only to the relative motions involved, which are entirely independent of colour. This assumption is uncontroversial and was the logical conclusion from the literature. Second, colour has since been empirically demonstrated to have no effect whatsoever on movement stability in a coordinated rhythmic movement task (Mechsner and Knoblich 2004). Colour can thus serve as a neutral cue to the participant that they are currently moving so as to produce the relevant information. The signal is not separated in either space or time from the information in the motion (as traditional knowledge of results or performance methods tend to be) nor does it interfere with or transform that information.

The following experiment set out to test whether coordination feedback can drive learning. We trained 5 participants to produce 90° mean relative phase using coordination feedback generated using Algorithm A (see Appendix) over five sessions and assessed their performance without feedback in Baseline and Post-training sessions at 0°, 90° and 180°. We compared this group to 5 participants who performed the same number of trials but with no feedback. We hypothesized that coordination feedback would be effective at improving performance, that only the Feedback group would learn (c.f. Wilson et al. 2010) and that only performance at 90° would change (c.f. Wilson and Bingham 2008). We therefore predicted a three-way interaction between group, session and target relative phase.

Methods

Participants

Ten participants from Indiana University (5 men, 5 women, aged 18–35, normal or corrected-to-normal vision, naïve to the experimental question) participated. They were split into two groups of five, balanced so that Baseline performance at 90° was equivalent. Group 1 ('Feedback') received coordination feedback during training; Group 2 ('No Feedback') received no feedback but an equal exposure to the task. The experiment was conducted with ethical approval from the local ethics committee.

Procedure

Participants sat in front of a Dell 1.73 GHz PC, with the monitor set to a resolution of 1024 × 768 and a refresh rate of 60 Hz. A Logitech Force 3D Pro joystick was connected via USB to the PC. The joystick had its force feedback feature turned off, so there was no opposition to the participants' motion. The computer presented a display showing two dots, which were white on a black background, one above the other (see Fig. 1). The top dot was under the control of the computer, while the bottom dot was under the control of the participant via the joystick (all participants used their preferred, right hand). The dot amplitude was 300 pixels; at the viewing distance of 70 cm, this is ~7.5° visual angle. Stimulus presentation, data recording and all data analysis were handled by a custom Matlab toolbox written by ADW, incorporating the Psychtoolbox (Brainard 1997; Kleiner et al. 2007; Pelli 1997; http://psychtoolbox.org).

There were two assessment sessions (Baseline, Post-training) and five training sessions. These were spread over seven separate days (not necessarily consecutive but within a 4 week period).

In all sessions, the top dot was under the control of the computer. It oscillated from side to side at .75 Hz with amplitude ~7.5° visual angle, and each trial lasted 20 s. Participants moved the bottom dot from side to side using the joystick, attempting one of three target mean relative phases (0°, 90° or 180°). Participants were given a demonstration of the target relative phase prior to each block (an 8-s display of two dots moving at the target relative phase).

In the assessment sessions, participants viewed a demo of the target relative phase and then performed five trials with a target mean relative phase of 0°, 180° and 90°,

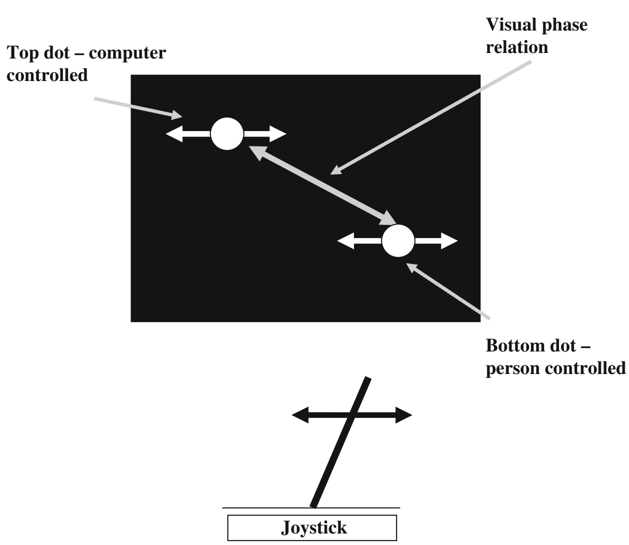

Fig. 1 A schematic of the experimental set up. The *bottom dot* was moved from side to side by the participant moving the joystick from side to side. During training the bottom dot changed colour (to *bright green*) if the participant was at the target relative phase ± the error tolerance

blocked and presented in that fixed order (total of 15 20 s trials). The first trial of each block was practiced (with online feedback), and the data were not analysed; there was no feedback for the four analysed trials.

In each of five training sessions, participants performed ten 20-s trials with a target mean relative phase of 90°, for a total of 50 trials over five separate days. In each trial, online coordination feedback was provided to the Feedback group by changing the colour of the person-controlled dot from white to green when the participant was moving at 90°, ± an error bandwidth. This was controlled using Algorithm A. The error bandwidth was *faded* across sessions; in the first, it was set to 40° so that any performance between 50° and 130° triggered the colour change. The bandwidth was decreased in each session to 30°, 20°, 15° and 10°, respectively, to drive continued improvement at the action task. Data from these trials were not analysed. The No Feedback group also did 50 practice trials, but with no feedback.

Participants were instructed to view the demo and then move at the indicated mean relative phase. The Feedback group was additionally told that when the dot was green they were moving successfully and that the error bandwidth was decreased with each training session.

Data analysis

The two position time series from each trial were filtered using a low-pass Butterworth filter with a cut-off frequency of 10 Hz and numerically differentiated to yield a velocity time series. These were used to compute a time series of relative phase, the key measure of coordination between the two dots.

In order to assess the stability of the coordination over the course of a trial, we used a measure first introduced by Wilson et al. (2010), *proportion of time on task*. Movement stability is not independent of mean relative phase in human movement; this means that measures that simply assess overall movement variability (e.g. mean vector length (Batschelet 1981) or the standard deviation of mean relative phase) are confounded with the actual relative phase produced. These measures can only be interpreted in light of the error data. Coordination stability at, e.g., 90° can be artificially elevated if participants spend time at other locations (e.g. 0° or 180°), which they do—these transitions are one of the cardinal features of untrained performance at unstable coordinations (Kelso 1981, 1995). Wilson et al. (2005a, b) addressed this issue in detail and solved it by regressing mean vector length against absolute phase deviation and using the intercept as the estimate of 'movement stability at the target phase'. Proportion time on task is a more robust and direct solution to the problem. It is simply the proportion of the relative phase time series that falls within the range of the target phase ± a tolerance (here, set to 20°[2]), thus eliminating the confound. This measure ranges from 0 to 1 and validly measures stability of movement at the required relative phase in a single number (see also Wilson et al. 2010).

Results

We performed a repeated measures ANOVA on the proportion time on task data (tolerance = 20°) with Session (2 levels: Baseline, Post-training) and Phase (3 levels: 0°, 90° and 180°) as within subject factors and Group (2 levels: Feedback, No Feedback) as a between-subject variable. Any analyses that significantly violated sphericity are reported with Greenhouse-Geisser corrected degrees of freedom.

Refer to Fig. 2. There was a significant main effect of Phase ($F(2, 16) = 44.9$, $P < .01$), with Session not reaching significance ($P = .067$), and significant two-way interactions between Session × Group ($F(1,8) = 15.4$, $P < .01$) and Session × Phase ($F(1.13, 9.04) = 12.8$, $P < .01$), with Phase × Group not quite reaching significance ($P = .052$). Crucially, however, these effects were all modified by the predicted significant Session × Phase × Group interaction ($F(2,16) = 16.9$, $P < .01$). All of the improvement as a function of training occurred at the trained relative phase of 90° for the Feedback group only. Participants who received coordination feedback therefore successfully and significantly improved their ability to maintain a 90°-coordination. This improvement did not generalize to either 0° or 180°, in line with Wilson and Bingham (2008) who established that learning 90° entails learning a novel information variable that is not used to produce the already stable coordinations. The No Feedback group showed no improvement at any mean relative phase.

Discussion

The perception–action approach to coordinated rhythmic movement requires experimenters to treat perceptual information as a critically important component of the task dynamic. In line with this approach, we have developed a new method for providing the augmented feedback necessary for learning novel coordinated rhythmic. This *coordination feedback* does not alter or remove the visual information about the coordination (the relative direction of motion). Other methods, such as visual metronomes (Tallet et al. 2008; Zanone and Kelso 1992a, b, 1997) and Lissajous figures (e.g. Debaere et al. 2004; Lee et al. 1995; Maslovat et al. 2009; Temprado and Swinnen 2005; Wenderoth and Bock. 2001; Wenderoth et al. 2002) all alter or remove this information. Training therefore takes place under different task/informational conditions than normal performance of a coordinated rhythmic movement, and this has consequences. For example, Kovacs et al. (2009) established that Lissajous feedback eliminates the bistability that is *the* hallmark phenomenon of coordinated rhythmic movement in humans (Kelso 1981, 1995). Participants in their experiment were able to quickly produce any target relative phase using a Lissajous figure as feedback to control their performance, because these figures transform the information used to perform the coordination to a form that can be stably perceived (c.f. Bogaerts et al. 2003; Wilson et al. 2005a, b). Converging evidence comes from Debaere et al. (2003), who found that different neural pathways were involved in the presence or absence of these types of augmented visual feedback.

Our work is currently focused on probing the composition and organization of the intrinsic task dynamic, primarily the identity of the perceptual information involved in generating the key phenomena in this task (Wilson et al. 2010; Wilson and Bingham 2008). We are also investigating how this task dynamic is altered by the process of learning (Wilson and Bingham 2008) as well as ongoing development of a perception–action model of this task (Bingham 2004a, b). We were therefore motivated to develop a method for presenting the augmented feedback required for learning in this task without the informational alterations entailed by other methods. The basic concept of coordination feedback is to compute whether the person is currently within a specified error bandwidth of the target relative phase; if so, the colour of the stimulus they are controlling on the screen is changed. The colour is changed back if they slip outside the specified range, and the range can be altered psychometrically to drive continued improvement. We used a colour change, because there it has been demonstrated that colour per se has no effect whatsoever on movement stability (Mechsner and Knoblich 2004); it could therefore neutrally signal success or failure. We suggest two algorithms for producing the required effect and tested the method using Algorithm A to establish that this feedback can drive learning. Participants given this feedback were indeed able to learn to produce 90°, suggesting that this method is indeed as effective as extant methods.

The learning did not generalize to either 0° or 180°, which can be accounted for by the results of Wilson and

[2] We have previously tested data using a wide range of error bandwidths; the only change is a main effect, where tighter error bandwidths lead to overall lower scores (Wilson et al. 2010). We therefore do not find any evidence that the chosen bandwidth alters the pattern of results (c.f. Bahrick et al. 1954): we choose 20° as an intermediate conventional range.

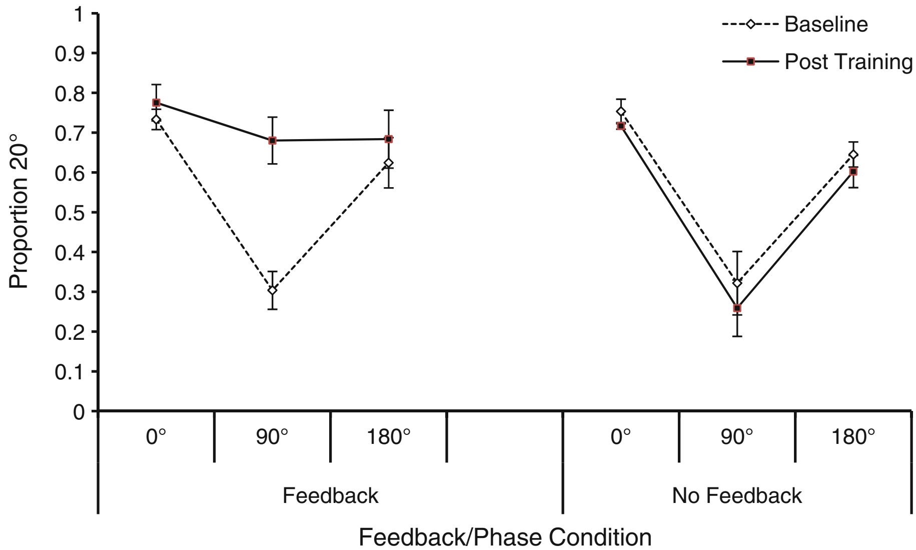

Fig. 2 Proportion of time spent within 20° of the target mean relative phase across the two sessions (Baseline: *solid lines*; Post-training, *dotted lines*) and for the two Feedback groups. *Error bars* show the standard error of the mean. Participants who received feedback learned to produce highly stable movements at 90°; this improvement did not generalize to other coordinations. Participants who did not receive feedback failed to improve at all

Bingham (2008), who established that learning to produce 90° in this task entails learning to use novel information (relative position) to coordinate and control the movement. This information is not used at 0° or 180°, where the use of relative direction already allows for stable movements; 90° is therefore informationally encapsulated after training. The fact that the current experiment showed no generalization of learning suggests that we have not disturbed this basic task dynamic, one of the goals of developing this method. Now that we have established that the method works, future research will investigate this in more detail by training other coordinations and then perturbing information variables as in Wilson and Bingham (2008) to identify what information is being used to produce which coordinations.

Augmented feedback is generally considered to be required in this type of task—people do not tend to spontaneously acquire 90° (for example), because they are unable to move at 90° long enough to allow the required perceptual learning. The control group in the current experiment received extensive practice at 90°, but no help identifying when they were moving correctly, and thus failed to learn this coordination at all. Guidance is clearly required, and the proposed method provides this guidance by cueing the presence of the necessary information in a neutral manner. Transformed feedback is therefore not required for learning in this task; coordination feedback produces equivalent learning via a more task-appropriate process than either visual metronomes or Lissajous figures.

The proposed method of coordination feedback was motivated by our perception–action approach to coordinated rhythmic movement, as instantiated in Bingham's model (Bingham 2004a, b). The method is straightforward to implement, does not alter the overall perception–action task dynamic and is effective at allowing people to acquire a novel coordination. We advocate this method as ideally suited for any experiment, in which the role of perceptual information or the nature of the learning process itself is the focus. Any algorithm that produces the basic perceptual effect (colour changing as a function of success or failure within a given error bandwidth) will work; we describe two such algorithms in Appendix. Training via these methods will, we believe, contribute to the ongoing development of a fully perception–action approach to learning a novel coordinated movement.

Appendix: coordination feedback algorithms

In this section, we describe two algorithms to implement coordination feedback. Algorithm A is the best solution for a situation where there is a reference target (i.e. a prespecified oscillator) and was used in the current experiment to produce the colour change. Algorithm B is still of use, however, especially in bimanual experiments where there is no reference target. Pilot work for the current experiment used Algorithm B to generate the feedback, which succeeded in driving learning.

Algorithm A: compute virtual target dots

This algorithm takes advantage of our standard experimental task, which requires participants to move a dot on a monitor at some mean relative phase to a computer controlled dot. The computer controlled dot's position is therefore a determined (sine) function of time, and it is trivially easy to generate two virtual dots moving according to the same function as the dot to be tracked, plus or minus some mean relative phase. This allows participants to be leading or lagging and still be getting the feedback (of course, if the experimenter had a preference, the feedback could be toggled to only occur in one direction). Once one knows precisely where the person should be at that instant in time, one then tests to see whether the person is within that specified error range from that location and toggle the colour accordingly. This check takes about 10 lines to implement in Matlab and no significant time to execute, making it viable for real-time feedback.

Algorithm B: compute relative phase online

The other method is to compute an estimate of relative phase in real time. If the dots are moving at the target relative phase (plus or minus some error bandwidth) then the colour of the dot is toggled. This method is noisier, but does not require a reference signal; we describe it here, because it will be of use to research involving bimanual movements.

The phase of an oscillator is computed (after normalizing the velocity and position) as

$$\Phi = \mathrm{atan}(\mathrm{velocity}/\mathrm{position}) \tag{1}$$

and the relative phase is simply the difference of the phases of the two oscillators. Position is straightforward, as it is the kinematic variable most commonly recorded directly. Velocity, however, must be derived via numerical differentiation; this amplifies noise, and hence position data is usually low-pass filtered beforehand (something not reliably possible in real time). Differentiation is an averaging process that requires position data from at least three time steps (depending on the algorithm), providing the velocity at the middle time step. Offline analysis allows the algorithm to be centred on the time step in question; computing this in real time means that the algorithm must be centred on a time step from the recent past. This introduces a small constant temporal lag in the velocity computation, i.e. the resulting time series is phase lagged relative to where it should be by an amount proportional to how far back in time the algorithm is centred. Finally, the computation of phase requires certain assumptions (that the required frequency and amplitude of movement are being maintained). To the extent that this is not the case, the estimate of phase and hence relative phase will be inaccurate.

These problems can be ameliorated in several ways, although never entirely removed:

1. *Minimize the number of data points included in the differentiation algorithm*. The basic trade off is that the more data points you include the better estimate of the current velocity you can get, but this estimate is for further back in time. Three data points is the absolute minimum; an acceptable estimate of velocity can be computed using five data points and a central difference algorithm (see Press et al. 2007). Pilot data for the current study successfully used this method. Placing the centre back two samples at 60 Hz created a lag in the velocity estimate of ~33 ms. There was no evidence that this created any significant difficulties for participants.
2. *Alter the differentiation routine*. Differentiation is essentially a process of computing a weighted average of the amount of change in position for a given amount of time, over several discrete samples of position. There are various differently shaped weighting functions available; for instance central difference algorithms weight the centre displacement the most and the weights quickly drop off on either side. This drop-off can be shaped to suit the user's needs (Press et al. 2007).
3. *Sample position at a higher rate*. The current experiment sampled position at 60 Hz, a limitation caused by the screen refresh rate. It is possible to sample hardware faster than the screen refresh rate with an asynchronous process (e.g. Culmer et al. 2009). This then allows one to sample position multiple times and compute velocity, phase and finally relative phase before the next screen refresh rate. This technique could also then be used to test whether any lag in the feedback from other implementations has any consequences for behaviour. Modern computer hardware should have no particular problems executing this in real time, if programmed carefully.

References

Bahrick HP, Fitts PM, Briggs GE (1954) Learning curves—facts or artifacts? Psychol Bull 54(3):256–268

Batschelet E (1981) Circular statistics in biology. Academic Press, NY

Bingham GP (2001) A perceptually driven dynamical model of rhythmic limb movement and bimanual coordination. In: Proceedings of the 23rd annual conference of the cognitive science society. Lawrence Erlbaum, Mahwah, pp 75–79

Bingham GP (2004a) A perceptually driven dynamical model of bimanual rhythmic movement (and phase perception). Ecol Psych 16(1):45–53

Bingham GP (2004b) Another timing variable composed of state variables: phase perception and phase driven oscillators. In: Hecht H, Savelsbergh GJP (eds) Advances in psychology 135: time-to-contact. Elsevier, Amsterdam, pp 421–442

Bingham GP, Schmidt RC, Zaal FTJM (1999) Visual perception of relative phasing of human limb movements. Percept Psychophys 61(2):246–258

Bingham GP, Zaal FTJM, Shull JA, Collins D (2000) The effect of frequency on visual perception of relative phase and phase variability of two oscillating objects. Exp Brain Res 136:543–552

Bogaerts H, Buekers MJ, Zaal FTJM, Swinnen SP (2003) When visuo-motor incongruence aids motor performance: the effect of perceiving motion structures during transformed visual feedback on bimanual coordination. Behav Brain Res 138:45–57

Brainard DH (1997) The Psychophysics Toolbox. Spat Vis 10:433–436

Buekers MJ, Bogaerts HP, Swinnen SP, Helsen WF (2000) The synchronization of human arm movements to external events. Neurosci Lett 290:181–188

Culmer PR, Levesley MC, Mon-Williams M, Williams JHG (2009) A new tool for assessing human movement: the kinematic assessment tool. J Neurosci Meth 184(1):184–192

Debaere F, Wenderoth N, Sunaert S, Van Hecke P, Swinnen SP (2003) Internal vs. external generation of movements: differential neural pathways involved in bimanual coordination performed in the presence or absence of augmented visual feedback. Neuro Image 19:764–776

Debaere F, Wenderoth N, Sunaert S, Van Hecke P, Swinnen SP (2004) Changes in brain activation during the acquisition of a new bimanual coordination task. Neuropsychologia 42:855–867

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 Psych 51(1):1–9

Hajnal A, Richardson MJ, Harrison SJ, Schmidt RC (2009) Location, but not amount of stimulus occlusion influences the stability of visual coordination. Exp Brain Res 199(1):89–93

Haken H, Kelso JAS, Bunz H (1985) A theoretical model of phase transitions in human hand movements. Biol Cybern 51(5):347–356

Kelso JAS (1981) On the oscillatory basis of movement. Bull Psychon Soc 18:63

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

Kleiner M, Brainard D, Pelli DG (2007) What's new in Psychtoolbox-3? Perception, 36, ECVP Abstract Supplement

Kovacs AJ, Buchanan JJ, Shea CH (2009) Using scanning trials to assess intrinsic coordination dynamics. Neurosci Lett 455:162–167

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

Li Y, Levin O, Carson RG, Swinnen SP (2004) Bimanual coordination:constraints imposed by the relative timing of homologous muscle activation. Exp Brain Res 156:27–38

Maslovat D, Brunke KM, Chua R, Franks IM (2009) Feedback effects on learning a novel bimanual coordination pattern: support for the guidance hypothesis. J Mot Behav 41(1):458–464

Mechsner F, Knoblich G (2004) Do muscles matter for coordinated action? J Exp Psych Hum Percept Perf 30(3):490–503

Pelli DG (1997) The VideoToolbox software for visual psychophysics: transforming numbers into movies. Spat Vis 10:437–442

Press WH, Teukolsky SA, Vetterling WT, Flannery BP (2007) Numerical recipes: the art of scientific computing, 3rd edn. Cambridge University Press, NY

Rosenbaum DA, Dawson AA, Challis JH (2006) Haptic tracking permits bimanual independence. J Exp Psych Hum Percept Perf 32(5):1266–1275

Schmidt RA, Lee TD (1999) Motor control and learning: a behavioral emphasis. Human Kinetics, Champaign

Schmidt RC, Carello C, Turvey MT (1990) Phase transitions and critical fluctuations in the visual coordination of rhythmic movements between people. J Exp Psych Hum Percept Perf 16(2):227–247

Tallet J, Kostrubiec V, Zanone PG (2008) The role of stability in the dynamics of learning, memorizing and forgetting new coordination patterns. J Mot Behav 40(2):103–116

Tallet J, Kostrubiec V, Zanone PG (2010) Proactive transfer of learning depends on the evolution of prior learned task in memory. Hum Move Sci 29(3):349–368

Temprado JJ, Swinnen SP (2005) Dynamics of learning and transfer of muscular and spatial relative phase in bimanual coordination: evidence for abstract directional codes. Exp Brain Res 160:180–188

Temprado JJ, Swinnen SP, Carson RG, Tourment A, Laurent M (2003) Interaction of directional, neuromuscular and egocentric constraints on the stability of preferred bimanual coordination patterns. Hum Move Sci 22:339–363

Wenderoth N, Bock O (2001) Learning of a new bimanual coordination pattern is governed by three distinct processes. Mot Cont 1:23–35

Wenderoth N, Bock O, Krohn R (2002) Learning a new bimanual coordination pattern is influenced by existing attractors. Mot Cont 6:166–182

Wilson AD, Bingham GP (2008) Identifying the information for the visual perception of relative phase. Percept Psychophys 70(3):465–476

Wilson AD, Bingham GP, Craig JC (2003) Proprioceptive perception of phase variability. J Exp Psych Hum Percept Perf 29(6):1179–1190

Wilson AD, Collins DR, Bingham GP (2005a) Perceptual coupling in rhythmic movement coordination—stable perception leads to stable action. Exp Brain Res 164(4):517–528

Wilson AD, Collins DR, Bingham GP (2005b) Human movement coordination implicates relative direction as the information for relative phase. Exp Brain Res 165:351–361

Wilson AD, Snapp-Childs W, Bingham GP (2010) Perceptual learning immediately yields new stable motor coordination. J Exp Psych Hum Percept Perf. doi:10.1037/a0020412

Wimmers RH, Beek PJ, Van Wieringen PCW (1992) Phase transitions in rhythmic tracking movements: a case of unilateral coupling. Hum Move Sci 11:217–226

Zaal FTJM, Bingham GP, Schmidt RC (2000) Visual perception of mean relative phase and phase variability. J Exp Psych Hum Percept Perf 26:1209–1220

Zanone PG, Kelso JAS (1992a) Evolution of behavioral attractors with learning: nonequilibrium phase transitions. J Exp Psych Hum Percept Perf 18(2):403–421

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

Zanone PG, Kelso JAS (1994) The coordination dynamics of learning: theoretical structure and experimental agenda. In: Swinnen S, Heur H, Massion J, Casaer P (eds) Interlimb coordination: neural, dynamical and cognitive constraints. Academic Press, San Diego

Zanone PG, Kelso JAS (1997) Coordination dynamics of learning and transfer: Collective and component levels. J Exp Psych Hum Percept Perf 23(5):1454–1480