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RESEARCH NOTE

Stability of rhythmic visuo-motor tracking does not depend on relative velocity

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Abstract It is well established that the in-phase pattern of bimanual coordination (i.e. a relative phase of 0°) is more stable than the antiphase pattern (i.e., a relative phase of 180°), and that a spontaneous transition from antiphase to in-phase typically occurs as the movement frequency is gradually increased. On the basis of results from relative phase perception experiments, Bingham (Proceedings of the 23rd annual conference of the cognitive science society. Laurence Erlbaum Associates, Mahwah, pp 75–79, 2001; Ecol Psychol 16:45–53, 2004; Advances in psychology 135: time-to-contact. Elsevier, Amsterdam, pp 421–442, 2004) proposed a dynamical model that consists of two phase driven oscillators coupled via the perceived relative phase, the resolution of which is determined by relative velocity. In the present study, we specifically test behavioral predictions from this last assumption during a unimanual visuo-motor tracking task. Different conditions of amplitudes and frequencies were designed to manipulate selectively relative phase and relative velocity. While the known effect of phase and frequency were observed, relative phase variability was not affected by the different conditions of relative velocity. As such, Bingham's model assumption that instability in relative phase coordination is brought about by relative velocity that affects the resolution of the perceived relative phase has been invalidated for the case of rhythmic unimanual visuo-motor tracking. Although this does not rule out the view that relative phase production is constrained by relative phase perception, the mechanism that would be responsible for this phenomenon still has to be established.

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Introduction

Since the seminal studies of Kelso (1981, 1984), the relative stability between different patterns of bimanual coordination has been extensively studied to investigate the constraints acting upon the coordination of interlimb movement. The in-phase pattern of coordination (i.e. a relative phase of 0°) was typically found more stable than the antiphase pattern (i.e., a relative phase of 180°), and spontaneous transitions from antiphase to in-phase were typically observed as the movement frequency was gradually increased.

Although neuromuscular correlates of those behavioral principles have been clearly identified (e.g., Carson 2005; Carson and Kelso 2004; Swinnen 2002), similar principles were also found under the sole influence of visual coupling, as in interpersonal coordination (Schmidt et al. 1990, 1998; Temprado and Laurent 2004; de Rugy et al. 2006) and in unimanual visuo-motor tracking of a movement on a screen (Wimmers et al. 1992; Stins and Michaels 2000; Buekers et al. 2000).

This motivated Bingham and colleagues to conduct a set of studies showing that perception of the variability of the relative phase between two balls moving on a screen matches behavioral results: the antiphase pattern was judged more variable than the in-phase pattern, and relative phase was judged more variable as the movement frequency increased (Bingham et al. 1999, 2001; Zaal et al. 2000). On the basis of those results, Bingham (2001, 2004a, 2004b) proposed a dynamical model that captures the results of both behavioral and perception studies. Central to this model is the coupling of two phase driven oscillators via the perceived relative phase, the resolution of which is determined by relative velocity. In the present study, we specifically test behavioral predictions from this last assumption of the model, i.e., that instability in relative phase coordination is brought about by relative velocity that affects the resolution of the perceived relative phase. This was achieved by manipulating selectively relative phase and relative velocity during a unimanual visuo-motor tracking task.

Bingham's model is as follows:

$$\ddot{x}_i + b\dot{x}_i + kx_i = c\sin(\phi_j)P_{ij}$$
$$\ddot{x}_j + b\dot{x}_j + kx_j = c\sin(\phi_i)P_{ji} \quad (1)$$

where x_i and ϕ_i are the position and phase of oscillator i, respectively, and the dots denote the first and second derivatives. Each oscillator is driven by the perceived phase of the other oscillator multiplied by a term P representing perceived relative phase:

$$P_{ji} = \mathrm{sign}\big(\sin(\phi_i)\sin(\phi_j) + \alpha(\dot{x}_i - \dot{x}_j)N_t\big) \quad (2)$$

P (i.e. $\pm$ 1) is the sign of the product of the two drivers incremented by a Gaussian noise term with a variance that is proportional to the velocity difference between the oscillators.

In the absence of noise, $P = +1$ ensures an in-phase pattern of coordination, whereas $P = -1$ ensures the opposite (antiphase) pattern. While the velocity difference is minimal during the production of the in-phase pattern of coordination between oscillatory movements of similar amplitude (Fig. 1b1), it is oscillating at a maximal amplitude for the antiphase behavior (Fig. 1b2); a noise term that is function of this difference (Fig. 1c2) will therefore affect P (Fig. 1d2) and the stability of the resulting behavior. As the velocity signals increase with frequency, so do the velocity difference and the resulting noise, leading to a further increased variability of the behavior. Note that the use of non-normalized velocity in Eq. 2 is crucial here, since normalizing velocity would prevent the increase in variability the model was precisely designed to reproduce. These features are illustrated in Fig. 2a together with predictions from Bingham's model in response to our selective manipulation of relative phase and relative velocity. This selective manipulation was achieved via the modulation of the amplitude of one of the two oscillations only: By multiplying the amplitude of one movement by three, the velocity difference obtained during an in-phase behavior (Fig. 1b3) is similar to that of the antiphase behavior performed with similar amplitudes (Fig. 1b2). According to Bingham's model, those two conditions should therefore produce similar variability profiles (Fig. 2a). Furthermore, the velocity difference obtained during an antiphase coordination performed with different amplitudes (Fig. 1c4) is higher than that obtained with similar amplitudes (Fig. 1 c2). According to Bingham's model, the variability of the behavior should therefore be higher in the former condition as compared with the latter (Fig. 2a). If the mechanisms involved in the studied coordination are independent of the relative velocity, however, our manipulation of movement amplitude should have little effect on the behavior; i.e., the known effects of phase and frequency should be observed, but different amplitudes should not affect relative phase variability (Fig. 2b).

We tested those predictions during a unimanual visuo-motor tracking task that permitted to keep the amplitude of the participants' movement constant while manipulating solely the amplitude and frequency of the target to track (either in-phase or antiphase).

Materials and methods

Six participants (four males and two females, aged 21–28) volunteered for this experiment. All were right handed with normal or corrected to normal vision. Participants were naive to the purpose of the experiment. They all gave informed consent prior to experiment, which was approved by the local ethics committee and conformed to the Declaration of Helsinki.

Each participant sat in a chair 70 cm from a computer display positioned at eye level. With their right hand, participants grasped a handle fixed to a rotating horizontal shaft (instrumented to record angular displacement at a sampling rate of 100 Hz) adjacent to the ulna. Pronation–supination movement resulted in the higher part of the handle to move right–left from the middle position defined by the vertical (forearm mid-prone).

The angular displacement of the handle controlled by participants was displayed online on the screen as a linear horizontal displacement of a white ball moving in the same direction as the higher part of the handle. An amplitude A1 of 3.4 cm (corresponding to an angular displacement of the handle of 62°) was prescribed by two thin vertical lines between which the participants were required to oscillate. Four centimeters above the "handle" ball was a "target" (also white) ball moving according to an imposed sinusoidal horizontal displacement. The white balls (1.7 cm diameter) were presented on a dark background. To ensure

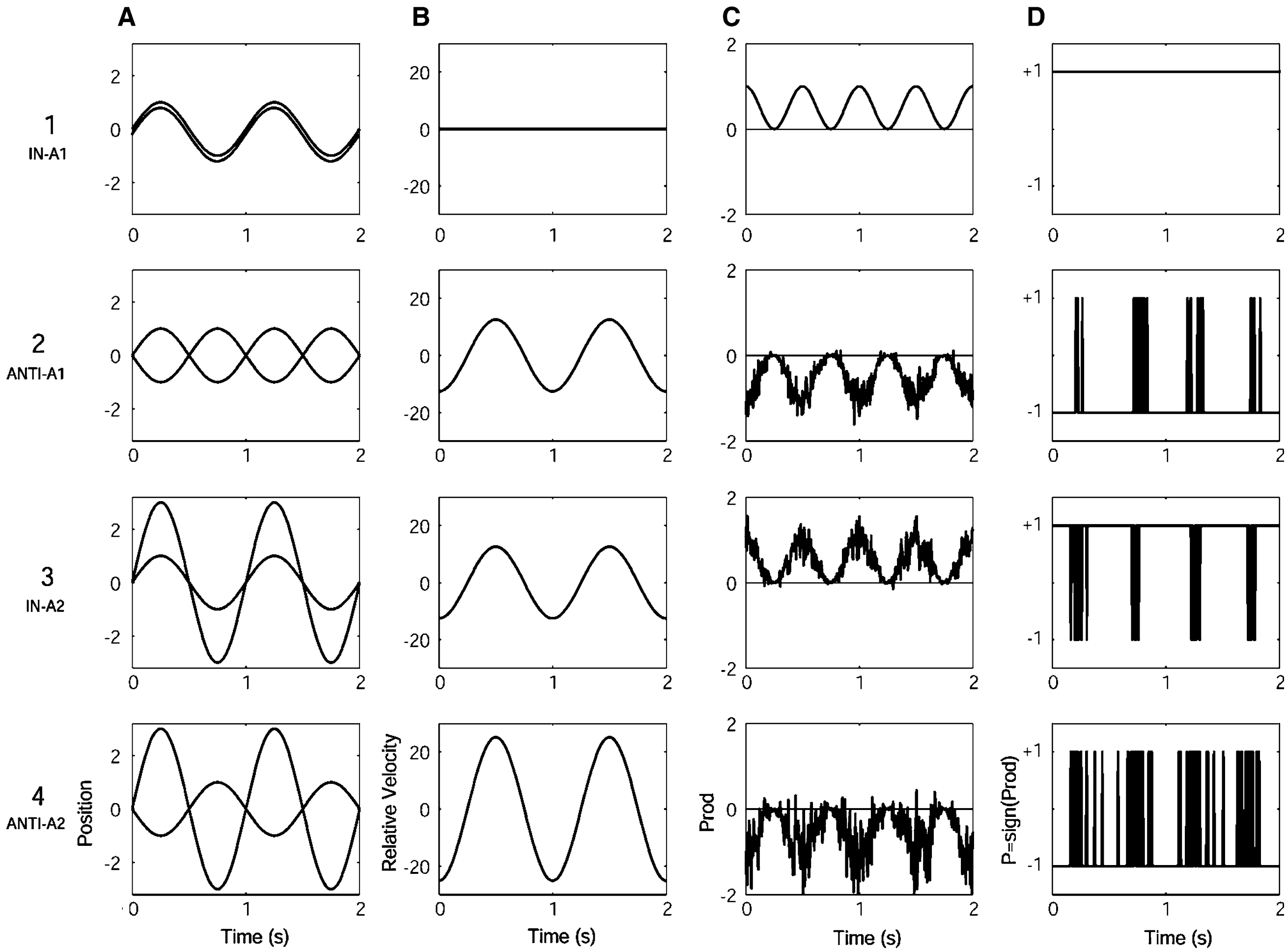

Fig. 1 **a** The positions (in arbitrary unit) of two oscillatory objects for the combinations of two conditions of relative phase [in-phase (*IN*) and antiphase (*ANTI*)] and amplitude (*A1* same amplitudes; *A2* one oscillation has an amplitude of three times the other). *Rows 1–4* correspond to condition *IN-A1*, *ANTI-A1*, *IN-A2*, and *ANTI-A2*, respectively. **b–d** Corresponding components of the coupling function in Bingham's model (Eq. 2). **b** Relative velocity ($\dot{x}_i - \dot{x}_j$); **c** product (prod) of the drivers incremented by a Gaussian noise with a variance proportional to the velocity difference (i.e., $\text{prod} = \sin(\phi_i)\sin(\phi_j) + \alpha(\dot{x}_i - \dot{x}_j)N_t$, with $\alpha = 0.0015$); **d** sign of prod (i.e., *P* in Eq. 2)

that only the stimulus displayed on the screen could be seen, the experiment was performed in the dark and participants wore soldering glasses. This visual display was designed to be as close as possible to that reported in the studies conducted by Bingham and colleagues on the perception of relative phase (Bingham et al. 1999, 2001; Zaal et al. 2000).

Participants were instructed to synchronize their oscillation (handle ball) either *in-phase* (IN) or *antiphase* (ANTI) with the oscillation of the target dot. In the IN condition, the handle ball had to move in the same direction as the target ball, and in the ANTI condition, it had to move in the opposite direction. While the amplitude of the handle ball's displacement was always prescribed at 3.4 cm, the amplitude of the target's displacement was either 3.4 cm (condition A1) or three times 3.4 cm (i.e, 10.2 cm, condition A2). Three frequencies were employed: 0.75, 1.25, and 1.75 Hz. After a few practice trials, the acquisition session consisted of five trials of 35 s performed in each of the 12 conditions [phase (2) × amplitude (2) × frequency (3)], presented in a fully randomized order.

Continuous relative phase was determined in phase space, i.e., the space spanned between position and velocity for each oscillation. The angular velocity obtained by differentiation of angular position was normalized by dividing the velocity signal by the mean frequency. Next, the phase angles were computed for each sample of oscillatory movement as the arctangent of the position and velocity. Mean circular relative phase ψ was then determined using circular statistics (Fisher 1993). To this end, the cosine and sine of the difference between the phase angle for the handle and the target were averaged separately, and ψ was obtained as the arctangent of their ratio (for more detail,

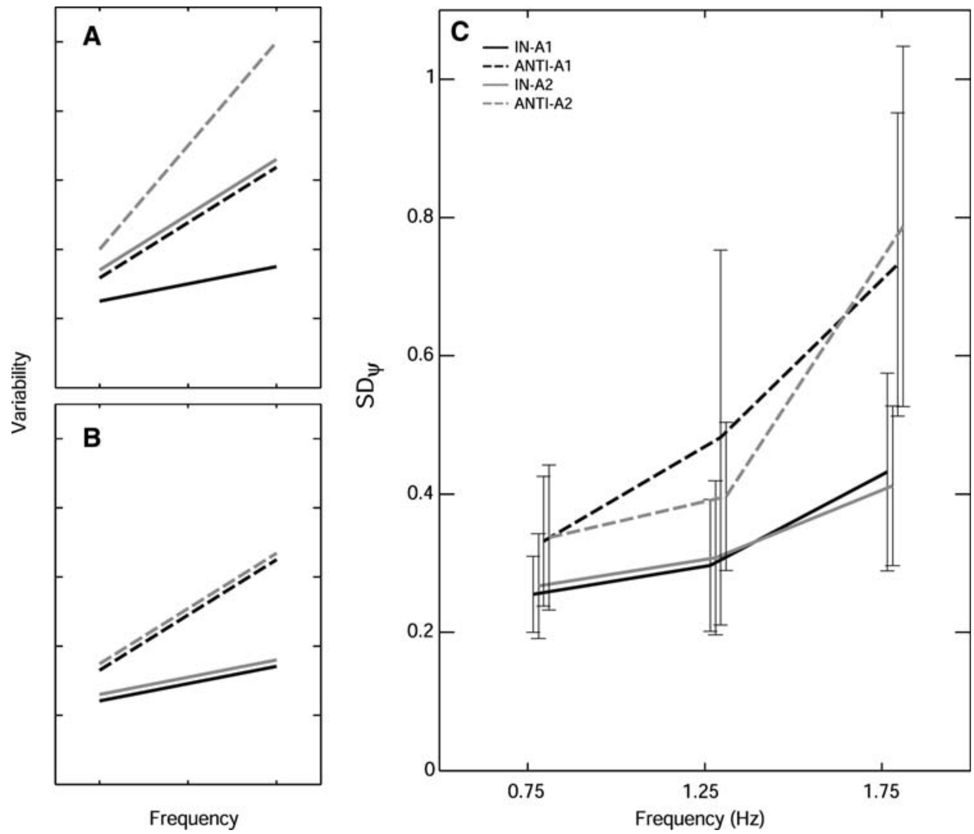

Fig. 2 Predicted (**a**, **b**) and effective (**c**) variability of the relative phase presented as a function of frequency for the different experimental conditions of phase and amplitude. **a** Qualitative prediction based on a variability that scales with relative velocity (i.e., Bingham's model). **b** Qualitative prediction based on a variability that does not depend on relative velocity (i.e, the known effects of phase and frequency only are displayed). **c** Experimental results ($SD\psi$). *Plain lines* represent the in-phase (*IN*) and *dashed lines* the antiphase (*ANTI*) conditions, while *dark lines* represent conditions of similar amplitudes (*A1*) and *gray lines* conditions in which one oscillation has an amplitude of three times the other (*A2*). *Error bars* represent the standard deviations

see Russell and Sternad 2001). A measure of dispersion of circular relative phase, uniformity *U*, was calculated according to Fisher (1993). As this measure is bounded by 0 and 1 and is nonlinear with respect to the distribution around the mean relative phase angle, it is converted into a measure of dispersion $SD\psi$ that varies approximately linearly between 0 and infinity according to:

$$\mathrm{SD}\psi = (-2\log_e U)^{1/2}$$

As in the linearly computed standard deviation measure high values of $SD\psi$ denote high variability, and low values indicate low variability.

Relative phase variability $SD\psi$ was averaged over the five trials performed under the same experimental condition, and analyzed using three-way repeated measures ANOVA (phase × amplitude × frequency). When a significant effect was obtained, the proportion of total variability attributable to the factor concerned was reported as the value of partial eta-squared (η^2) (see Pierce et al. 2004, for information about partial eta-squared measures).

Results

Figure 2c shows that the variability of the relative phase was higher for the antiphase than for the in-phase pattern of coordination; that this variability increased with the frequency of movement; and that this increase was higher for the antiphase than for the in-phase pattern of coordination. The three-way repeated measures ANOVA (phase × amplitude × frequency) conducted on $SD\psi$ revealed a strong effect for the phase ($F(1, 5) = 30.24$, $P = 0.003$, $\eta^2 = 0.86$), for the frequency ($F(2, 5) = 23.06$, $P = 0.006$, $\eta^2 = 0.92$), and a significant interaction between them ($F(1, 5) = 23.19$, $P = 0.006$, $\eta^2 = 0.92$). No effect, however, was found for the amplitude ($F(1, 5) = 0.05$, $P = 0.83$) or for the other interactions (all $F < 0.65$ and $P > 0.56$). Figure 2c confirms that our manipulation of amplitude had little effect on the behavior, and that the obtained variability profiles correspond to a coordination mechanism that does not depend on relative velocity (Fig. 2b) rather than on the coordination mechanism proposed in Bingham's model (Fig. 2a).

Discussion

Bingham (2001; 2004a, b) proposed a perceptually driven dynamical model of bimanual coordination that consists of two phase driven oscillators coupled via the perceived relative phase, the resolution of which deteriorates as a function of relative velocity. In the present study, we specifically test behavioral predictions from this last assumption, which is implemented Eq. 2 with a noise term that is proportional to the relative velocity. The rationale for this was twofold: first the noise term in Eq. 2 was supposed to reflect known sensitivities to the direction of optical velocities (De Bruyn and Orban 1988; Snowden and Braddick 1991). And second, because relative velocity is higher for antiphase than for in-phase coordination and increases with frequency, its magnitude already matches variability results of both behavioral and perception experiments. In the absence of influence of neuromuscular coupling between hands for our unimanual case, and while the motor component of the task was carefully kept constant (because the amplitude of the movement to perform was constant, the motor command had to be virtually the same for the different conditions of relative phase and target amplitude performed at the same frequency), our experiment was designed to promote as much as it possibly could the influence of the a perceptual component as proposed in Bingham's model. Yet, we failed to observe an influence of relative velocity on the variability of the behavior, and must conclude that the coupling term proposed in Bingham's model does not reflect the coupling that operates in rhythmic visuo-motor tracking. Although this does not rule out the view that relative phase production is constrained by relative phase perception, the mechanism that would be responsible for this phenomenon still has to be established.

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