When to dwell and when to move: finding comfort in variability

Ignasi Cos[1,2], Benoît Girard[1,2] and Emmanuel Guigon[1,2]
[1]UPMC, Univ Paris 06, UMR 7222, ISIR, Paris, France
[2]CNRS, UMR 7222, ISIR, Paris, France [ignasi.cos@isir.upmc.fr]

Understanding how we predict time intervals and define their motor content is a non-trivial problem. For example, professional baseball batters adjust the duration and speed of their strike movement according to their prediction of the interval between the ball release and arrival, expert waltz dancers synchronize the end of each loop on beat with the music, as do orchestra players guided by the tempo of their director's baton. Irrespective of the differences in behaviour, these tasks share the common goal of predicting a temporal interval and of producing a set of controlled movements that fit in within. Related to this, experimental evidence shows that the motor system can estimate time intervals [1]. However, the variability of these estimates increases with time, making predictions increasingly inaccurate as the predicted duration expands [1,2]. Despite this limitation, skilled musicians or dancers seldom fail in their predictions. How is this possible?

To address this issue, we performed a psychophysical experiment in which nine subjects were instructed to tap repetitively with their right finger on a rubber band. At each trial, they had to tap either at their preferred frequency, or guided by a metronome at 0.5, 1, 1.5, 2 or 2.5 Hz, and at one of three different amplitudes (default, small, large). They were instructed to synchronize arrival on the rubber band with the metronome cue. We recorded the position of their fingertip with a Codamotion system. Data was parsed to identify dwell (*DT*, contact), movement (*MT*) and period (*T*) intervals (Fig. 1A).

The results we describe next concern the movements performed at the default amplitude only. Subjects organized their tapping cycles by producing well-identified dwell (range 0.03-1.4 s) and movement (range 0.25-1.95 s) intervals [3]. As the period between acoustic cues increased, dwell and movement intervals scaled up accordingly (Fig. 1B). In other words, subjects chose to maintain the percentage of duration of their dwell and movement intervals constant with respect to the overall period. What is the criterion leading to this specific solution? May this specific scaling provide an optimal temporal accuracy?

To answer these questions, we assessed whether the subjects made an optimal use of their own temporal uncertainty for movement synchronization. For each subject, we first modelled temporal variability as $\sigma_X = \alpha_X X + \beta_X$ with $X = DT, MT$ [4]; coefficients were obtained by linear regression (Fig. 2A). In general, the temporal variability of *DT* was larger than that of *MT* in 7/9 subjects (Fig. 2A, *top*), comparable for one subject, and lower for the remaining subject (Fig. 2A, *bottom*). Interestingly, the *DT* and *MT* of free frequency trials were consistent with those obtained for imposed frequencies (Fig. 2A). Second, we calculated the optimal *MT* predicted by minimization of overall period variability using $\sigma_T^2 = \sigma_{DT}^2 + \sigma_{MT}^2$ (see below for covariance). The predicted *MT* was close to the observed *MT* for all the subjects (two are illustrated in Fig. 2B). For 7/9 subjects, the variance of the period observed experimentally was close to the predicted minimal period variance, when the covariance between dwell and movement is taken into account (two subjects are shown in Fig. 2C). Remarkably, the model predicted not only the average behavior of 7/9 subjects accurately (Fig. 3), but furthermore the behavior of the two outliers, despite their behavioral distinctiveness (Fig. 3, *dotted* and *dashed*). In conclusion, this shows that the model may capture different strategies, as a response to the different patterns of dwell and movement variability of each individual subject.

Overall, these results strongly suggest that movement synchronization relies on an optimal choice between dwell and movement intervals, based on the temporal uncertainty of the two processes. This result is consistent with a previous study showing that subjects can maximize time-dependent monetary gains related to reaching movements despite uncertainty related to the duration of these movements [4].

References 1. Ivry RB (1996) Curr Opin Neurobiol 6(6):851-857 — 2. Hazeltine E, Helmuth LL, Ivry RB (1997) Trends Cogn Sci 1(5):163-169 — 3. Repp BH, Su YH (2013) Psychon Bull Rev 20(3):403-452 — 4. Hudson TE, Maloney LT, Landy MS (2008) PLoS Comput Biol 4(7):e100013.

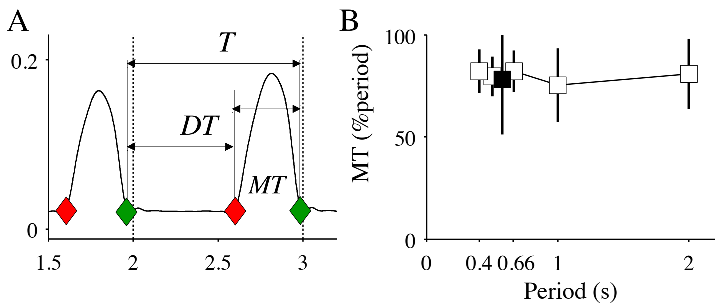

Figure 1. **A**. Finger position (m) during tapping at 1 Hz as a function of time (s); (*green*) time of contact; (*red*) movement onset; (*dashed line*) metronome. *DT* dwell interval (between contact and onset), *MT* movement interval (between onset and contact), and *T* period interval (between successive contacts). **B**. *MT* as a percentage of the period, as a function of period of the metronome (average and sd across subjects).

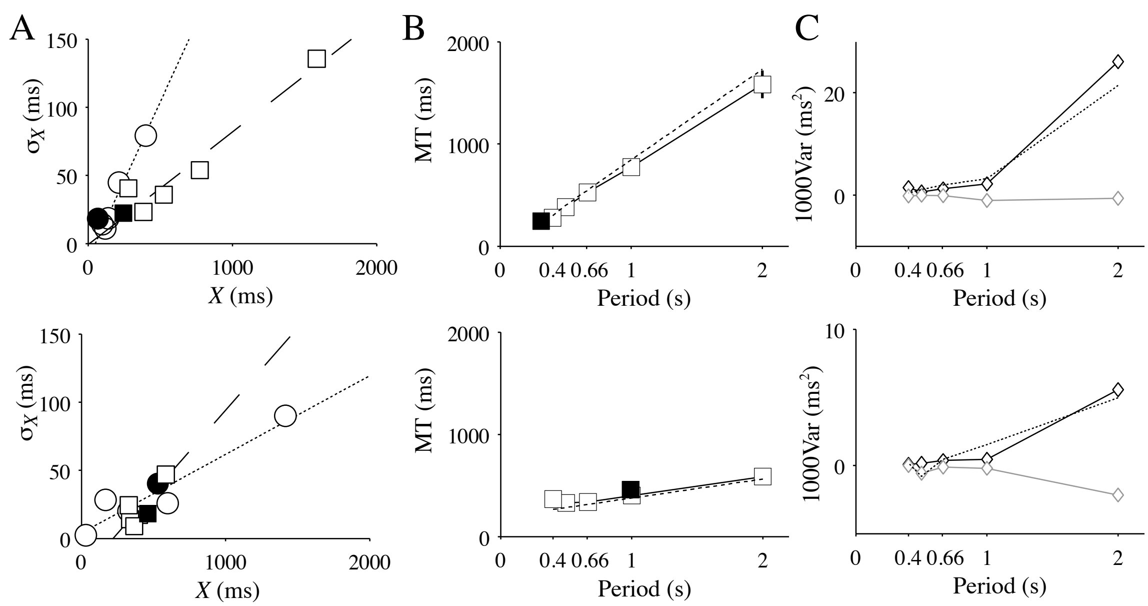

Figure 2. **A**. (*top*) Standard deviation of *X=DT,MT* (*circle*, *square*) as a function of *X=DT,MT* for a representative subject. *Dotted* and *dashed* lines are regression lines for *DT* and *MT*. Data have been pooled across all imposed frequencies. Free frequency is indicated by a plain symbol. (*bottom*) Same as *top* for another subject. **B**. (*top*) Observed (*square*) and predicted (*dashed line*) *MT* for the subject in **A**, *top*. (*bottom*) Same as *top* for subject in **A**, *bottom*. **C**. (*plain black*) observed variance of the period interval; (*plain grey*) covariance of *DT* and *MT*; (*dotted*) variance predicted by the model + 2×observed covariance.

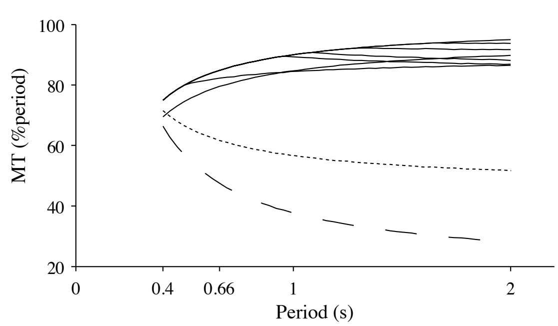

Figure 3. MT, expressed as a % of the period predicted by the model, for each individual subject. In solid line, the MT of the 7 subjects with larger temporal variability for *DT* than for *MT* (see Fig. 2A, *top*); in dotted line the one subject with comparable variability for DT and MT; and in dashed line the one subject with lower variability for *DT* than for *MT* (see Fig. 2A, *bottom*).