Synthesis of asymmetric movement trajectories in timed rhythmic behaviour by means of frequency modulation

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Abstract

Results from different empirical investigations on gestural aspects of timed rhythmic movements indicate that the production of asymmetric movement trajectories is a feature that seems to be a common characteristic of various performances of repetitive rhythmic patterns. The behavioural or neural origin of these asymmetrical trajectories is, however, not identified. In the present study we outline a theoretical model that is capable of producing syntheses of asymmetric movement trajectories documented in empirical investigations by Balasubramaniam, Wing, and Daffertshofer (2004). Characteristic qualities of the extension/ flexion profiles in the observed asymmetric trajectories are reproduced, and we conduct an experiment similar to Balasubramaniam et al. (ibid.) to show that the empirically documented movement trajectories and our modelled approximations share the same spectral components. The model is based on an application of frequency modulated movements, and a theoretical interpretation offered by the model is to view paced rhythmic movements as a result of an unpaced movement being “stretched” and “compressed”, caused by the presence of a metronome. We discuss our model construction within the framework of event-based and emergent timing, and argue that a change between these timing modes might be reflected by the strength of the modulation in our model.

Keywords

Asymmetric movement trajectories, model, frequency modulation

1. Introduction

There are two dominant traditions in behavioural studies of movement timing: *the information processing approach* and *the dynamical systems approach*, also referred to as *the nonlinear oscillator approach* (cf. Beek et al., 2000; Wing & Beek, 2002; Balasubramaniam, 2006). The information processing approach deals with *discrete* aspects of timing behaviour, and the variables of major interest are time intervals, i.e., intertap intervals and asynchronies. On the other hand, rather than studying discrete synchronisation events, the dynamical systems approach investigates *continuous* movement trajectories, dynamic pattern formation, and the evolution of performance with time. In the dynamical systems approach, timing is considered to be an emergent property of the organisational principles that govern a particular coordinated action, whereas in the information processing approach, time is considered a mental abstraction that depends on central timing processes, represented independently of any particular effector system (cf. Wing & Beek, 2002). These different approaches in studies of movement timing are closely related to the theoretical framework that distinguishes between two forms of timing control: emergent timing and event-based timing (Delignières & Torre, 2011; Delignières et al., 2004, 2008; Repp & Steinman, 2010; Robertson et al., 1999; Schöner, 2002; Spencer & Ivry, 2005; Spencer et al., 2003; Zelaznik et al., 2002). As stated by Delignières and Torre (2011, p. 313): "…, the essential difference between event-based and emergent timing is in the involvement or noninvolvement, respectively, of an abstract and effector independent representation of the time intervals to produce." Very interesting discussions related to whether event-based and emergent timing can coexist or not in a single task, are found in Repp and Steinman (2010) and Delignières and Torre (2011). In Delignières and Torre (ibid.) we read that some timing tasks tend to favour event-based timing (i.e., discrete finger tapping), some others emergent timing (i.e., continuous circle drawing or

forearm oscillations), whereas other tasks appear more ambiguous. Moreover, they state: “Air tapping (in which taps are performed in the air, without contact with any surface) seems to present this ambiguity” (ibid., p. 313).

An interesting empirical investigation that emphasises the importance of combining the dynamical systems approach and the information processing accounts of movement timing, is presented by Balasubramaniam, Wing, and Daffertshofer (2004). As a starting point for their study they comment that whereas previous investigations of paced repetitive movements with respect to an external beat have *either* emphasised the form of movement trajectories (the dynamical systems approach) *or* timing errors made with respect to the external beat (the information processing approach), - the question of *what kinds* of movement trajectories *assist timing accuracy* has not previously been addressed. Following up this question Balasubramaniam et al. construct a new experimental paradigm aimed at investigating how various timing tasks are reflected in different movement trajectories. This experiment involves synchronisation or syncopation with an external auditory metronome, and they show that the nervous system produces trajectories that are *asymmetric* with respect to time and velocity in the out and return phases of the repeating movement cycle (see Figure 1).

Figure 1. Example of asymmetric trajectory. Illustration of asymmetric movement trajectory in the experiment of Balasubramaniam et al. This trajectory is the result of a subject being instructed to synchronise the minimal points of the movement of the index finger to the beats of a metronome. (Adapted from Fig.1 in Balasubramaniam et al., 2004, p. 130.)

Moreover, they find that this asymmetry is task specific and independent of motor implementation details (flexion vs. extension), and, furthermore, that the degree of asymmetry in the flexion and extension movement times is positively correlated with timing accuracy. On the basis of their findings, they suggest that "movement asymmetry in repetitive timing tasks helps satisfy requirements of precision and accuracy relative to a target event" (ibid., p.129). Thus, they point at an interesting result which is related to research questions that are basic to both of the two dominant traditions in behavioural studies of movement timing. Correlation between asymmetric movement trajectories and timing accuracy has also been discussed in Balasubramaniam (2006), Delignières and Torre (2011), Elliott et al. (2009), Torre and Balasubramaniam (2009), and is given additional support by results from empirical investigation on synchronisation of the index finger with various visual pacing sequences (Hove and Keller, 2010). Empirical studies of drummers´ movements in the performance of different rhythms and grooves also show that the movement of the drumstick produces trajectories that are asymmetric (cf. Dahl, 2004, 2006, 2011; Waadeland, 2003, 2006, 2011). Results from different investigations on gestural aspects of timed rhythmic movements thus indicate that the production of asymmetric movement trajectories is a feature that seems to be a common characteristic of various performances of repetitive rhythmic patterns. The behavioural or neural origin of these asymmetrical trajectories is, however, not identified.

In the present paper we outline a theoretical model that is capable of producing syntheses of characteristic features of the asymmetric movement trajectories documented in the empirical investigation of Balasubramaniam et al. (2004), and we conduct a spectral evaluation of our model to show that the observed movement trajectories and our modelled approximations share the same spectral components. The model is based on an application of frequency modulated movements and is constructed by means of a synthesis technique developed earlier by the author, which has shown to be useful in making syntheses of

rhythmic expression in music (Waadeland, 2001). It should at this point be noted that in all of the conditions in the experiment of Balasubramaniam et al. (2004), the index finger made no contact with any surface during the movement trials. Thus, this experimental setup involves timing tasks that are considered to be ambiguous as to whether event-based or emergent timing is favoured in the performance (see Delignières & Torre, 2011). When we here propose a new model for the movement trajectories in the experiment of Balasubramaniam et al., we might therefore also generate some new thoughts concerning the relation between event-based and emergent timing. This will be discussed in the concluding sections of the paper.

2. The experiment of Balasubramaniam, Wing, and Daffertshofer

Before we present our model we take a closer look at some of the basic constituents of the empirical investigation of Balasubramaniam, Wing, and Daffertshofer. Their experimental setup is described in Balasubramaniam et al. (2004) and Balasubramaniam (2006), and is hereafter referred to as the BWD experiment. Briefly stated, the BWD experiment was designed in the following way (cf. Balasubramaniam et al., 2004, p. 131):

Subjects were instructed to synchronise their index finger movement to a metronome in two ways:

(i) Peak flexion on the beat: fON (i.e. to synchronise the minimal points of the movement to the beat)

(ii) Peak extension on the beat: eON (i.e. to synchronise the maximal points of the movement to the beat)

moreover, to syncopate:

(iii) Peak flexion off the beat: fOFF (i.e. flexing to strike (midway) between beats)

and, in an unpaced condition:

(iv) Subjects were instructed to oscillate their index finger at a comfortable frequency and amplitude in the absence of a metronome

In all of these conditions the index finger made no contact with any surface during the movement trials. The conditions (i) – (iii) were conducted with three different metronome frequencies; 1000 ms (1 Hz), 750 ms (1.33 Hz), 500 ms (2 Hz). The kinematics of the movement trajectories of the index finger were recorded by a motion capture system. Sample trajectories from each condition are shown in Figure 2 ((i), (ii), (iii) with metronome frequency 2 Hz). This figure is adapted from Fig. 1 in Balasubramaniam et al. (2004, p. 130).

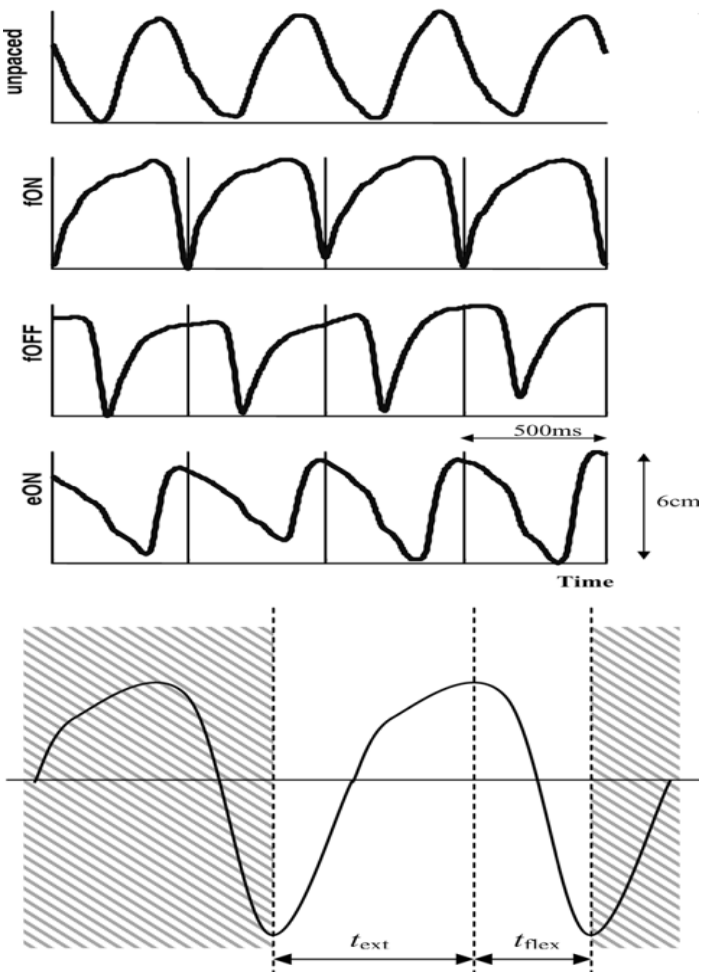

Figure 2. Visualising different asymmetries. Sample trajectories from each of the four conditions in the BWD experiment. At the top: Four cycles of displacement from a sample trial of a subject in the unpaced condition, followed by fON, fOFF, and eON. The vertical lines in fON, fOFF and eON

display the metronome event. The bottom illustration shows extraction of parameters from the asymmetric movement trajectories (t_{ext}, t_{flex}) in the fON condition. (Adapted from Balasubramaniam et al., 2004, p. 130.)

Looking at Figure 2 we notice that whereas the unpaced condition shows a sinusoidal like, close to symmetric movement trajectory, all of the kinematic profiles in the paced conditions show a marked asymmetry. Statistical tests of asymmetry carried out by BWD (ibid.) show that in general $t_{ext} > t_{flex}$ in the fON and fOFF conditions, and $t_{flex} > t_{ext}$ in the eON condition. It is also interesting to note that they find that all movement trajectories were more symmetrical with increasing frequency (ibid., p. 131). This is a result which is supported by findings in studies of a drummer´s performance of swing groove (Waadeland, 2011). In the unpaced condition BWD observe no significant differences in movement time or velocity between flexion and extension. Moreover, they draw attention to the fact that while fON and fOFF have similar extension/ flexion profiles, eON is different. This latter observation is especially interesting since eON is sometimes seen as an alternative strategy for syncopation fOFF (cf. Kelso et al., 1998).

Given this insight into characteristic features of the asymmetric movement trajectories demonstrated in the BWD experiment, we now turn to the construction of our model, aimed at making syntheses of these various asymmetries.

3. Development of the model

As documented in the BWD experiment, an unpaced oscillation of the index finger tends to create a sinusoidal, close to symmetric movement trajectory (cf. above and Balasubramaniam et al., 2004). Viviani (1990) stated that sine waves are easy to approximate by human movements, and are among the simplest predictable motions. Moreover, a symmetrical movement form has been applied in several modelling efforts that have

attempted to capture an oscillator description of finger movements (Kay et al., 1991), and as a starting point for the construction of the HKB model, the motion of the fingers are assumed to be sinusoidal (Haken et al. 1985, p. 349). Thus, it seems natural to represent an (idealised) unpaced oscillatory finger movement by a sine wave. Our particular choice of such a sinusoidal is expressed by the mathematical function:

(1) $y(t) = A[1 - \cos(2\pi f t)]$,

where t is time, f is the frequency of the finger movement, and A is the amplitude (2A is a measure of the finger´s maximum distance from the minimal value, 0). An illustration of the function in (1), with f = 2, is given in Figure 3.

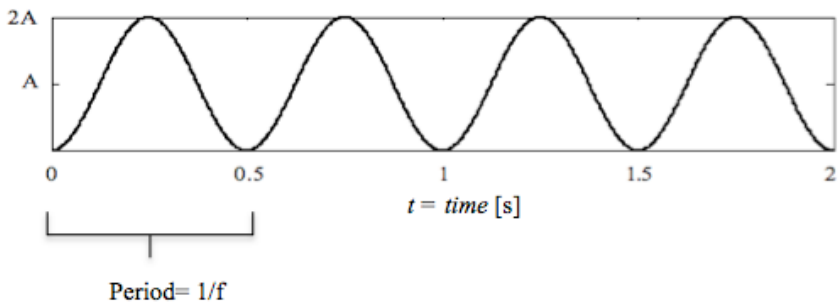

Figure 3. Model of unpaced movement. Graphic illustration of an idealised movement trajectory in the unpaced condition with frequency, f = 2. Time is displayed along the horizontal axis, and the finger´s vertical position is measured along the vertical axis.

When the finger is allowed to oscillate at a comfortable frequency and amplitude in the absence of a metronome, the finger movement exists *without any external interaction*, so to speak (i.e. unpaced), with any other sensation or task specific condition. However, this is not so in the paced conditions, where the subjects of the experiment are affected by sounds from the metronome and make efforts to synchronise their finger movement to the beat. As shown in the BWD experiment, this additional performance condition causes the movement trajectories to *change shape* in different ways. – One way to look at this is to say that as a result of additional timing constraints, the trajectory that in the unpaced condition is (close to) symmetric, is being “stretched” and “compressed” in various ways, attaining an asymmetric

form. Thus, compared to the unpaced condition, synchronisation to the metronome implies modulation of velocities and causes change in the *spectral properties* of the movement.

A well known technique of *sound* synthesis using various alterations or distortions of the frequency of an oscillator in order to achieve parameter control over the spectral richness of the sound, is *frequency modulation*, FM, pioneered by Chowning (1973). The most basic FM instrument consists of two sinusoidal oscillators interacting to give the output:

(2) $y(t) = A\sin[2\pi f_c t + d\sin(2\pi f_m t)]$.

A is the amplitude, f_c is commonly denoted *carrier frequency*, f_m is the *modulating frequency*, and d is the *peak frequency deviation* (cf., Chowning, 1973; or Dodge & Jerse, 1985). Looking at the output of the basic FM instrument, we observe that when $d = 0$, there is no modulation and the result is simply a sine wave with frequency f_c. This very situation resembles, at least *on a purely theoretical level*, the situation we are trying to establish for synthesis of movement trajectories in timed rhythmic behavior: When the metronome is absent, the finger oscillates freely and there is no modulation. The result of this is a sinusoidal movement trajectory. When, on the other hand, the metronome is present, modulation occurs and various deviations of frequency are created, resulting in different kinds of non-sinusoidal, asymmetric trajectories in the modeled situation (hopefully) approximating the trajectories in the BWD experiment.

Strongly motivated by this observation, we now set out to investigate to what extent the technique of frequency modulation, previously applied to synthesis of sound, may be transformed and adjusted to a strategy of synthesis where various paced conditions in timed rhythmic movements are regarded as *frequency modulations of an unpaced sinusoidal trajectory*. Before we start our model construction we now present a brief overview of a formerly developed synthesis technique based on frequency modulation of rhythms.

3.1. Rhythmic frequency modulation:

In Waadeland (2001) a new application of frequency modulation was presented which proved to be an interesting tool in making synthesis of rhythmic expression in music. By means of rhythmic frequency modulation (RFM) various simulations of rhythmic deviations typical of live performances of music were made as a result of continuous movement curves modulating each other. The basic RFM algorithm is defined on the basis of a combination of formulas (1) and (2) above, and is illustrated in the flowchart in Figure 4.

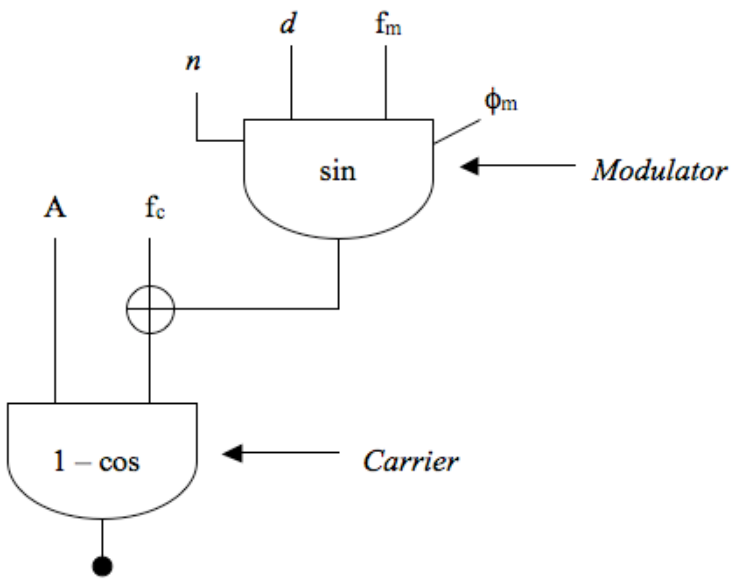

Figure 4. Flowchart for basic rhythmic frequency modulation.

The output of this RFM algorithm is given by the function:

$$(3)\quad y(t) = A[1 - \cos[2\pi f_c t + d\sin^n[2\pi(f_m t + \phi_m)]]]$$

where:

t = time

A = carrier amplitude

f_c = carrier frequency

f_m = modulator frequency

ϕ_m = modulator phase divided by 2π

d = peak frequency deviation = modulator amplitude (= "strength of modulation")

n = exponent of the modulating sine function

It should be noted that in our former construction of the various RFM syntheses (Waadeland, 2001) the idea was to make a model where rhythm performance was represented as a continuous unfolding through attack points (the onsets of rhythmic events), and to manipulate the timing of these onsets by means of frequency modulation of the modeled movement trajectories connecting the different attack points. The main interest at that time was therefore to construct a continuous model of characteristic aspects of expressive *timing*. In doing so, we noticed (ibid.) that many of the frequency modulated trajectories were, in different ways, characterized by various asymmetries. However, the very *shape* of the trajectories in the model was not, in our previous research, in focus. This situation is contrary to our focus in the present paper. – Now we wish to propose a model by which we can construct syntheses of characteristic features of empirically documented movement trajectories in timed rhythmic behavior, and we will in our forthcoming development of the model discuss how various investigated timing aspects may be implemented in our synthesis.

3.2. Adjusting the RFM parameters

(i) As a first step in developing the RFM technique into a model for asymmetric movement trajectories we note that the trajectories in the BWD experiment are decomposed into two states of movements: extension vs. flexion (see Figure 2). These movement states define two temporal intervals of different length, t_{ext} and t_{flex}, whereby each movement cycle is divided in two. We find that we are able to achieve a such decomposition of each cycle of the RFM trajectory by means of algorithm (3) if the frequency of the modulator is half the frequency of the carrier, i.e.:

(4) $f_m = \frac{1}{2} f_c$

(ii) As demonstrated in Figure 3, the period of the unpaced ($d = 0$), sinusoidal movement trajectory in the RFM algorithm (3), is $1/f_c$. Likewise, we observe from Figure 2 that the paced BWD trajectories are periodic-like with period $1/f_{metro}$ (f_{metro} = frequency of the metronome). We have underlined in the previous that a fundamental premise in our model construction is to regard the various paced conditions as different frequency modulations of an unpaced sinusoidal trajectory. This implies that in our model construction *the frequency of the metronome in the paced conditions should equal the frequency of the carrier in our model*, thus, $f_{metro} = f_c$. As a consequence of this, our simulations of the BWD trajectories should be periodic(-like) with period $1/f_{metro} = 1/f_c$. To obtain this feature in the RFM synthesis, the effect of the modulator should be the same over every cycle of the carrier. On the basis of relationship (4) this is accomplished if the modulator is a positive function, i.e. the exponent, n, is an even number:

(5) $n = 2k$, where k is a natural number

At this point, in our initial model construction, we set $k = 1$, i.e. $n = 2$. Hence, we arrive at the following expression as our first candidate in the application of RFM synthesis as a model of asymmetric movement trajectories:

(6) $y(t) = A[1 - \cos[2\pi f_c t + d\sin^2[2\pi(\frac{1}{2}f_c\, t + \phi_m)]]]$

(iii) In Figure 2 we observe that fON and fOFF have similar extension/ flexion profiles, but the peak flexion of fOFF is temporally transposed (time shifted) compared to the peak flexion of fON. This is a direct consequence of the instructed performance condition of fOFF; flexing to strike midway between metronome beats. The extension/ flexion profile of eON is different, but also in this case Figure 2 illustrates that the peak extension and flexion are temporally transposed compared to fON. In order to obtain this in our synthesis there should

be implemented a temporal transposition in our model. To achieve this we include a time-shift, $t \rightarrow t - \delta$, where δ is a temporal transposition along the axis of time. Thus, we propose the following algorithm for making RFM simulations of the asymmetric BWD trajectories:

$$(7)\ y(t) = A[1 - \cos[2\pi f_c(t - \delta) + d\sin^2[2\pi(\tfrac{1}{2}f_c(t - \delta) + \phi_m)]]]$$

Note that the five parameters involved in this RFM synthesis are:

A = amplitude; which is a scaling factor corresponding to the magnitude (height) of the finger movement

f_c = carrier frequency = frequency of metronome in the paced conditions

d = peak frequency deviation; which is a measure of the "strength" of modulation

ϕ_m = modulator phase (divided by 2π); which contributes to defining the shape of the modulated trajectory

δ = temporal transposition along the time axis; reflecting the different task specific performance conditions fON, fOFF and eON

4. Synthesis of asymmetric movement trajectories by means of RFM

Applying the RFM algorithm in (7) we now demonstrate how each of the movement trajectories in the BWD experiment illustrated in Figure 2 may be simulated by applying frequency modulation of a sinusoidal movement. As noted in the previous, the unpaced condition generates a sinusoidal-like movement which is reflected in our model by an (idealised unpaced) unmodulated trajectory ($d = 0$). For each of the trajectories in Figure 2 illustrating the different paced conditions, the frequency of the metronome, $f_{metro} = 2$ [Hz] (period = 500 ms), and the height of the finger movement is approximately 6 [cm]. To simulate this, we set $f_{metro} = f_c = 2$ and A = 3. Hence, we are left with variations in *three parameters* in the RFM algorithm (7) when we demonstrate how the different BWD

trajectories may be approximated. These three parameters are d, ϕ_m and δ. As commented above, variations in ϕ_m contribute to different shapes of the modulated trajectory, and ϕ_m is, as such, an important parameter in the different RFM simulations. However, in order to pinpoint how different characteristic features of the trajectories corresponding to fON, fOFF and eON are reflected in specific changes in the parameters d and δ, we illustrate how each of these movement trajectories may be simulated by applying *the same value* of ϕ_m; ϕ_m = 0.25. Thus, the expression generating our syntheses of the various BWD trajectories in Figure 2 is the following ($A = 3$, $f_c = 2$, $\phi_m = 0.25$):

$$(8)\ y(t) = 3[1 - \cos[4\pi(t - \delta) + d\sin^2[2\pi((t - \delta) + 0.25)]]]$$
$$= 3[1 - \cos[4\pi(t - \delta) + d\cos^2[2\pi(t - \delta)]]]$$

We note that the formula (8) contains only *two parameters*: d (peak frequency deviation), and δ (temporal transposition along time axis). In the following we show how different choices of d and δ yield various approximations to the different BWD trajectories. An interpretation of d and δ and a discussion of how these parameters are related to the various performance tasks in the BWD experiment is given in section 6. Figure 5 illustrates the carrier and modulator that are applied in our RFM synthesis of the BWD trajectories.

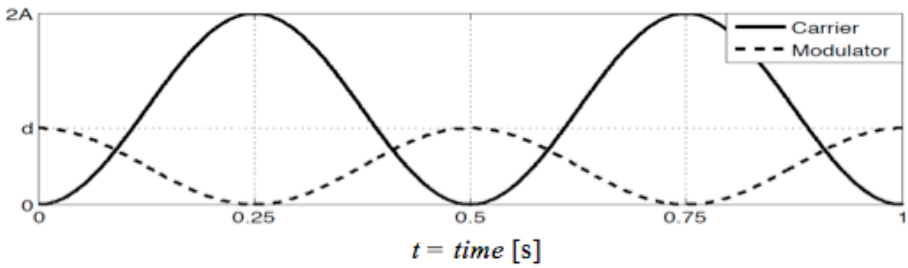

Figure 5. Illustration of carrier and modulator. A graphic representation of carrier: $y(t) = A[1 - \cos[4\pi t]]$, and modulator: $y(t) = d\cos^2[2\pi t]]$ that are used in the various FM simulations of the BWD trajectories in the following. (We have here set $\delta = 0$.) Note that d represents the maximal value for the effect of the modulator.

4.1. Simulation of fON

The simulations to follow, of fON, fOFF and eON, are all constructed by comparing the BWD trajectories with various graphs of the RFM algorithm in (8), resulting from different choices of d and δ. An FM simulation of the condition *peak flexion on the beat* is demonstrated in Figure 6 below.

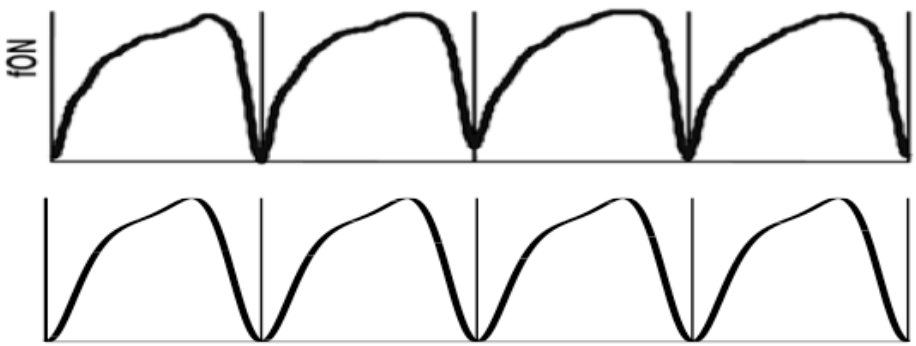

Figure 6. Example of an FM simulation of fON. At the top we see a sample trial of a subject in the fON condition (adapted from Balasubramaniam et al., 2004, p. 130), whereas the bottom illustrates an FM simulation (d = 1.5 and δ = 0.089). The vertical lines represent the metronome event.

The simulation in Figure 6 is constructed by means of the RFM algorithm in (8) by applying strength of modulation, d = 1.5, where after the FM-trajectory is transposed along the time axis in order to match the position of the peak flexion on the metronome event in the BWD sample trial. This is achieved with δ = 0.089 [s].

Visual inspection of Figure 6 reveals that our FM-simulation reflects the typical features of the BWD trajectory in the fON condition: We obtain an asymmetric movement trajectory with characteristic extension/ flexion profile, where $t_{ext} > t_{flex}$ and peak velocities (slope of movement curve) $v_{flex} > v_{ext}$.

4.2. Simulation of fOFF and eON

FM approximations of the trajectories related to the conditions *peak flexion off the beat* and *peak extension on the beat* are exemplified in Figure 7.

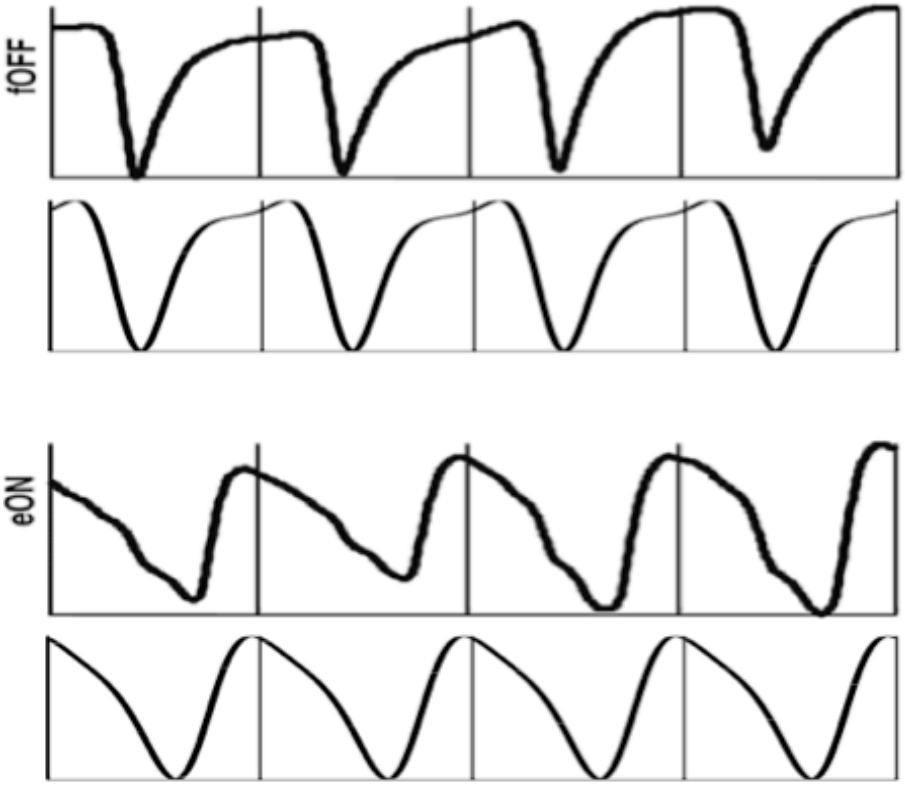

Figure 7. An illustration of FM simulations of fOFF and eON. The fOFF and eON trajectories show sample trials in the BWD experiment (Balasubramaniam et al., 2004, p. 130), our FM simulations are achieved by choosing $d = 1.8$, $\delta = 0.31$, and $d = -1.1$, $\delta = 0.23$ respectively.

4.2.1. The fOFF simulation

We notice that the sample of the fOFF trajectory in the BWD experiment has a somewhat "more flat" top than the fON trajectory (see Figure 2). In our RFM algorithm this is reflected in applying more strength to the modulation (larger d) in the fOFF-simulation as compared to the simulation of fON. Thus, the FM simulation in Figure 7 is obtained from (8) by choosing $d = 1.8$ (whereas $d = 1.5$ in the fON-synthesis in Figure 6). Moreover, in order to approximate the temporal position of the points of peak flexion, we apply a time shift, $\delta = 0.31$.

Comparing the fOFF trajectory and our approximation in Figure 7, we observe that our FM simulation reflects typical features related to asymmetry of the trajectory in the fOFF condition in BWD, and we achieve $t_{ext} > t_{flex}$ and peak velocities $v_{flex} > v_{ext}$. It is also interesting to note that, due to our choice of δ, characteristic *timing tendencies* are reflected in

this simulation, particularly that the peak flexion points are earlier than the midpoint between two metronome events (vertical lines in Figure 7). This is also typical in the fOFF situation in BWD, as Figure 7 illustrates.

4.2.2. The eON simulation

Visual inspection of Figure 7 shows that our FM simulation in this case reflects characteristic features of the BWD trajectory in the eON condition. In particular, our synthesis has a similar asymmetric shape as the eON trajectory, and we obtain $t_{flex} > t_{ext}$ and $v_{ext} > v_{flex}$, which is also the case in the eON condition of BWD. Moreover, due to our choice of δ, δ = 0.23, we are also able to simulate a characteristic timing feature in the eON condition: the peak extension is slightly earlier than the metronome signal (see Figure 7).

It is here also interesting to note that in order to achieve this specific timing profile by means of our RFM algorithm in (8), we have to choose a *negative* value of the peak frequency deviation, d. In our simulation in Figure 7 we have $d = -1.1$. We will return to a discussion of the role of d in relation to the different performance conditions in section 6.

5. Spectral evaluation of the model

By comparing graphs on the basis of *visual inspection* we have in the previous demonstrated how our various FM syntheses possess typical *qualities* of graphical shape that are in accordance with the different characteristic shapes of the corresponding trajectories in the BWD experiment. Obviously, it is also important to obtain some analytical measure, which, on a *quantitative* basis can tell us how good our FM simulations are. In order to achieve a closer look into that, we use a motion capture system to conduct an experiment similar to that of BWD, and apply FFT-analysis of the motion data in order to obtain insight

into the different spectra of the finger movements related to the various performance conditions. These spectra can then be compared to the output of an FFT-analysis of our FM simulations in order to reveal to what extent the empirical documented movement trajectories and our corresponding FM simulations share the same spectral properties. We now report some interesting results from this experiment:

5.1. Procedure

A subject performed repetitive right index finger movements synchronised with a metronome in accordance with the three performance conditions fON, eON and fOFF in the BWD experiment. The metronome was set to have the frequency 500 ms (2 Hz). The kinematics of the movement trajectories of the index finger were recorded at 400 Hz by an eight-camera Qualisys motion capture system. A marker was placed at the tip of the index finger. The analysis of the kinematic data was done in MATLAB.

5.2. Results

An FM simulation of the condition fON in our experiment is given in Figure 8 below.

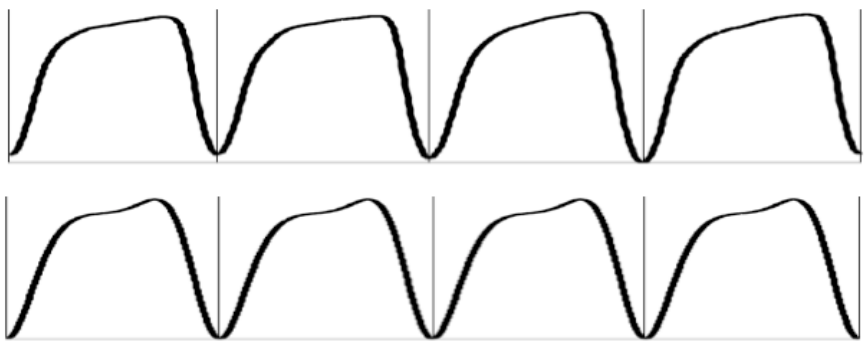

Figure 8. FM simulation of fON in our experiment. The upper trajectory shows the performance of the subject in the fON condition of our experiment, whereas the lower trajectory illustrates an FM simulation (d = 1.85, δ = 0.1).

Comparing Figure 8 with Figure 6, we notice that the movement trajectory in our experiment share the same characteristics as the corresponding trajectory in the BWD experiment. However, our subject makes the fON performance with a more flat top than the subject in the BWD setting. This is reflected in in the application of more strength to the modulation in the FM simulation of our fON performance as compared to the BWD performance (d = 1.85 in Figure 8, whereas d = 1.5 in Figure 6).

Applying MATLAB to carry out FFT-analysis of the motion data of the fON performance in our experiment and of our FM simulation, we are now able to compare the spectra of the empirical performance and our corresponding FM synthesis. Figure 9 illustrates how these spectra are related.

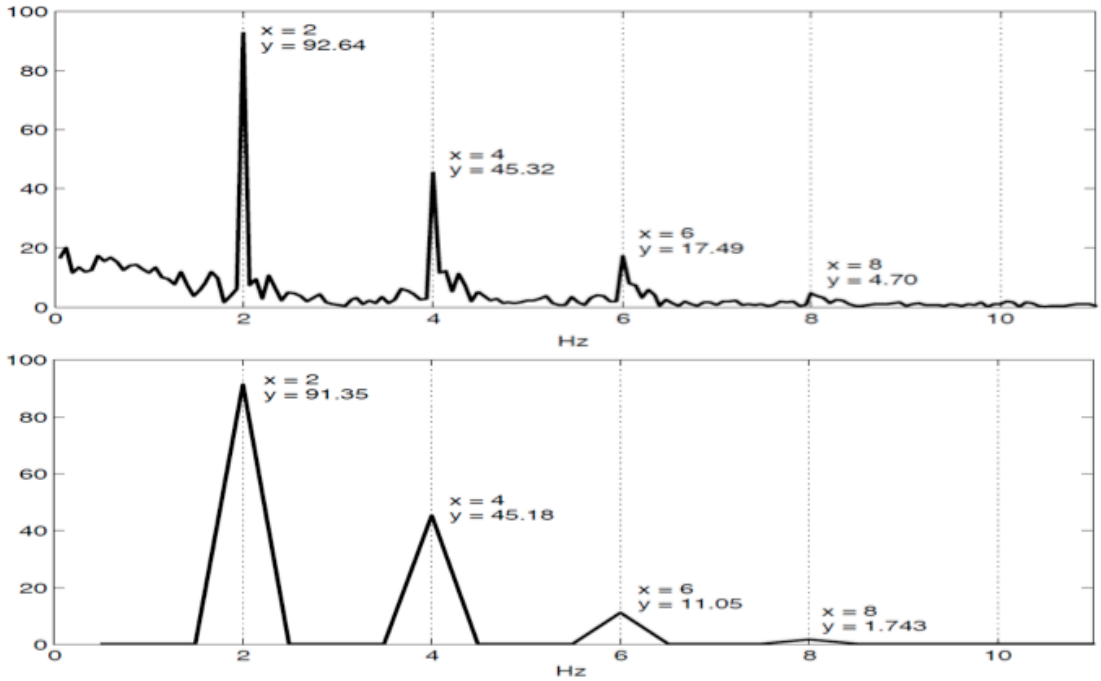

Figure 9. Comparison of spectra. Illustration of the spectra of an fON performance, metronome 2 Hz (upper graph), and an FM simulation of the performance, with strength of modulation: d = 1.85 (lower graph). Frequency is displayed along the horizontal axis, whereas the vertical axis displays relative magnitude of the amplitudes of the spectral components. Notice that the two spectra have components at the same frequencies: 2 Hz, 4 Hz, 6 Hz, 8 Hz.

Looking at Figure 9 it is interesting to note that our FM simulation has spectral components at the same frequencies as the fON performance: at 2 Hz, 4 Hz, 6 Hz and 8 Hz, and that the

relative magnitudes of the components in the FM approximation match quite well the relative magnitudes of the corresponding components in the fON performance. – At least this is the case for the two components with the largest amplitudes, at 2 Hz and 4 Hz, whereas the components at 6 Hz and 8 Hz in our simulation should have somewhat larger amplitudes to make an even better approximation. Moreover, we see that the metronome tempo, 2 Hz, is reflected in the spectral component with the largest amplitude. – Conducting FFT analyses of the eON and fOFF performances and our corresponding FM simulations also yield similar pictures as the one shown in Figure 9.

6. Discussion

In this paper we have presented a theoretical model that applies frequency modulation to reproduce characteristic features of empirically observed asymmetric movement trajectories arising from synchronising finger movements with a metronome. Given a fixed metronome frequency, all our simulations are obtained by varying only two parameters: d and δ. The parameter d represents the strength of the modulation, reflecting the degree of asymmetry. Moreover, we find that the mathematical sign of d is related to the *target direction* of the finger´s movement; $d > 0$: peak flexion to target (fON and fOFF), $d < 0$: peak extension to target (eON), and $d = 0$: no target (i.e. unpaced condition). Whereas the mathematical sign of d is linked to the direction of the *motor target*, the absolute value of d in combination with the parameter δ reflects the *timing target* of the synchronisation task. – If the movement of the index finger were pure sinusoidal (as in an idealised unpaced situation ($d = 0$)), the point of peak flexion and extension would be determined by δ alone (a temporal transposition of a sinusoidal function). However, when d is different from 0, the frequency modulation creates asymmetric trajectories, which affect the timing (peak flexion or extension

of the movements), and this is "adjusted" by various temporal transpositions, δ, in order to (to different degrees) hit the timing target (on or off the beat). Thus, the timing target is reached through an interplay between the parameters *d* and δ, reflecting an interaction between gestural aspects (*d*) and aspects of timing (δ) in the synchronisation task. – At this point it should be underlined that for each simulation of asymmetric movement trajectory, we have, so far, given *d* and δ constant values. This obviously makes our modelled trajectories static. Live performances of rhythm, on the other hand (whether in music or in different synchronisation tasks), are characterized by different fluctuations or deviations from static regularity. Therefore, in trying to implement more temporal features of rhythmic movements into our synthesis, a natural extension of our model would be to make the temporal transposition, δ, as well as the peak frequency deviation, *d*, functions of time. Moreover, it should be noted that BWD found that the movement trajectories were more symmetrical with increasing frequency (Balasubramaniam et al., 2004, p.131). Since asymmetry in our synthesis is constructed by non-zero values of *d*, this observed phenomenon could be simulated by making *d* a function of the carrier frequency, f_c, in such a way that the absolute value of *d* increases with decreasing f_c. Further empirical research is needed to investigate how our model should be developed to implement temporal features and account for the influence of frequency on the kinematic profiles.

As mentioned in the introduction of this paper, various research on timed rhythmic behaviour has identified two different modes of timing control: event-based and emergent timing. Event-based timing refers to the assumption that serial motor responses are triggered by a sequence of discrete cognitive events, provided by an internal timekeeper, cf. the well known model of Wing and Kristofferson (1973), which accounts very well for e.g. discrete finger tapping. In contrast, for tasks such as continuous circle drawing or forearm oscillations, the timing is assumed to be regulated on the basis of a different process, involving self-

sustaining oscillator properties of the effector system, without any cognitive representation of the temporal interval to be produced. This second timing mode is referred to as emergent timing. A number of experiments have been constructed to determine statistical signatures allowing for unambiguously identifying the nature (event-based vs. emergent) of the timing process involved in a given rhythmic activity. Delignières and Torre (2011) presented two frequently used approaches, based on autocorrelation and spectral analyses. Moreover, they (ibid.) conducted a very interesting experiment where they showed that air tapping is an example of a more ambiguous task where participants can exploit either the event-based or the emergent timing mode, or the two in alternation. Since air tapping is a timing task in all conditions of the BWD experiment, it is interesting to discuss our model within the framework of these two modes of timing.

The *unpaced* condition is in our model represented by the carrier function in the RFM algorithm (3), which is a pure sinusoid. A natural interpretation of the unpaced situation in our model is thus that an unpaced performance, as in the BWD experiment, involves emergent timing (as in continuous circle drawing and forearm oscillations). – Related to this it is interesting to know that Spencer et al. (2003) showed that instructing participants to perform air tapping by moving the index finger in a smooth, continuous manner induced the involvement of emergent timing and created sinusoidal-like movement trajectories. These findings of Spencer et al. support our interpretation of the model in the unpaced condition.

In the different *paced* situations of the BWD experiment the participants are under the influence of a metronome. Repp and Steinman (2010, p. 124) claim that “synchronization with a metronome requires event-based timing”, whereas Delignières and Torre (2011) disagree and argue that event-based timing is not determined by the presence of metronomic signals, but rather by the presence of cognitive events provided by an internal timekeeper

(ibid., p. 317). – In the following we argue that our model of the paced conditions may be interpreted as (at different times) a representation of both event-based and emergent timing.

A basic premise for our model construction is to view the various paced conditions in the BWD experiment as different frequency modulations of an idealised unpaced sinusoid. The frequency of the metronome is represented by the carrier frequency, and is, thus, considered to implement environmental input in the model.

6.1. Interpretation as event-based timing:

The participant has an explicit cognitive representation of the temporal interval to be produced, defined by the beats of the metronome. This internal representation of timing information is used to adjust the frequency of the oscillating index finger (which in the unpaced situation is f_c in the model) to the frequency of the metronome. Moreover, the participant emphasizes or accentuates the internalised metronome beats by giving them extra "weight" through acceleration towards the metronome event. In the model this is represented by frequency modulation, and gives rise to asymmetric movement trajectories simulating the findings in the BWD experiment. In this case the internalised central timekeeper is triggering a motor response: a frequency modulated sinusoid generated on the basis of the control strategies outlined above, and the timing is event-based. – It should here be noted that whereas the model of Wing and Kristofferson (1973) is based on autocorrelation of time intervals, i.e. discrete points in time, our model suggests that adjustments relative to a central timekeeper apply to *continuous* aspects of the motor response: the frequency of the oscillating finger and the degree of modulation.

6.2. Interpretation as emergent timing:

A metronome is present, but the participant has no *explicit* cognitive representation of the temporal interval to be produced. Our model proposes that there exists a continuous coupling between the oscillating limb and the metronome, represented by the carrier oscillator. This carrier oscillator is in varying degree, for different participants, being frequency modulated to mirror various asymmetries in the movement trajectories. If there is no modulation, synchrony with the metronome is obtained by performing a sinusoid (sinusoidal-like) movement as in the unpaced condition, based on the dynamical properties of the oscillating finger (cf. also Spencer et al., 2003). – If, on the other hand, modulation occurs, creating asymmetric movement trajectories reflecting an acceleration towards the metronome beats, temporal regularity in the performance arises from the consistency of the oscillator´s dynamical properties (cf. Scöner, 2002; Zelaznik et al., 2002), that might be due to the participant being used to, or trained to a particular embodied movement pattern, performed without the involvement of any abstract and effector independent representation of discrete points in time. In this case we have a situation where "movement dynamics may be considered as *serving* event-based timing … while it *generates* emergent timing" (Torre et al., 2010). – This situation could be compared to a musician rehearsing new technical challenges playing an instrument: In the beginning the musician has to use cognitive and mental representations of time and movement to trigger various motor actions, whereas after some time the musician has embodied a vocabulary of movement patterns which in a concert situation (hopefully) emerges from learned and, eventually, automatized organisational principles that govern the various coordinated actions required to play the instrument. – Seen in the light of this comparison, and on the basis of the experiment of Delignières and Torre (2011) showing that in air tapping different participants at different times exploit an event-based or emergent timing mode, it would be interesting to study air tapping over longer periods of performance

intervals, to investigate whether the participants tend to favour a performance exploiting event-based timing in the beginning of the performance and, to a larger degree, emergent timing in the end.

As mentioned in the previous, Spencer et al. (2003) showed that instructing participants to perform air tapping by moving the index finger in a smooth, continuous manner induced the involvement of emergent timing. In the same paper they also reported that instruction to pause briefly before each downstroke in the air tapping task induced event-based timing. The smooth, continuous condition created sinusoidal-like trajectories, whereas the intermittent tapping (with pauses) generated asymmetric movement trajectories. Related to this it is very interesting to know that Delignières and Torre (2011, p. 315) stated: "It is possible that during emergent epochs in air tapping the trajectory of the index finger should be smooth and harmonic, whereas during event-based epochs it should be more jagged, with the presence of systematic pauses before each downstroke." – Thus, emergent vs. event-based timing modes might be reflected in the degree of asymmetry of the movement trajectories. Since the BWD experiment showed that the movement trajectories were more symmetrical with increasing frequency, this might indicate that at low frequencies of air tapping event-based timing is the most dominant, whereas at higher frequencies emergent timing is to a larger degree exploited. – Moreover, since asymmetry in our model is represented by the strength of modulation, determined by the peak frequency deviation, d, this might also suggest that a change between the two modes of timing control, emergent vs. event-based timing, is reflected in the magnitude of the absolute value of d. – However, further research is needed to obtain more knowledge about these matters.

It should at this point be commented that at the present stage of our model construction the model has been developed to simulate gestural aspects of timed rhythmic behaviour, - the shape of the movement curves. The focus has therefore been on continuous

movements, periodicity, and the form of the trajectories. Also, the model is based on a coupling of oscillators, established as frequency modulation. Seen as such, the model in its present version might be regarded as closest related to the dynamical systems approach in studies of movement timing (cf. Beek et al., 2000; Wing & Beek, 2002). In future improvements of the model we will try to implement more temporal features, which is also likely to include characteristics of the information processing approach, e.g. various autocorrelation processes, but then probably rather to adjust the frequency of the oscillation and degree of modulation, instead of adjusting time intervals.

7. Conclusion

Applying a synthesis technique based on frequency modulation, we have in the present paper been able to make simulations of all of the asymmetric movement trajectories in the BWD experiment. Our FM simulations reflect characteristic kinematic features of the BWD trajectories in each of the conditions, fON, fOFF and eON, and we have demonstrated that the empirically investigated movement trajectories and our modelled approximations share the same spectral components. A basic idea in our model construction has been to regard paced rhythmic movements as a result of an unpaced movement, - which in our model is represented by a sinusoidal oscillator with frequency f_c, being frequency modulated by another oscillator, caused by the presence of a metronome with frequency f_{metro}. The strength of the modulation is determined by the peak frequency deviation, *d*, and different choices of *d* are reflected in different degrees of asymmetries in the movement curves. – The unpaced condition of the BWD experiment is in our model represented by no modulation ($d = 0$), in which case f_c is seen to emerge from dynamical properties of the effector system. On the other hand, in the various paced conditions f_c adjusts to the tempo of the metronome, which in the model is

represented by the idealised situation $f_c = f_{metro}$. In this case f_{metro} implements environmental input in the model. Whether f_c in this situation can be interpreted as resulting from discrete/ cognitive or dynamic processes, and to what extent the environmental influence is internalised, might be seen as dependent on the magnitude of the absolute value of *d*. – Larger absolute values of *d* give rise to more asymmetric trajectories (reflecting acceleration towards the metronome events), whereas when *d* is close to zero, a symmetric-like movement trajectory is generated. Thus, supported by the findings of Spencer et al. (2003), and Delignières and Torre (2011) reported above, a possible interpretation is that a change between the two timing modes (event-based vs. emergent) is reflected by the strength of modulation in our model. Following up on this idea, it could be interesting to investigate how the magnitude of the absolute value of *d* is related to various statistical signatures of the two timing modes. If it were possible to find a significant relation between these parameters, it might also be possible to dissociate between the two forms of timing control on the basis of the strength of modulation in the FM synthesis. – Finally, it should be commented that the model might provide an interesting entry point for the discussion of anchoring dynamics (non-linear oscillator models with specific anchor points (in time), here: the metronome beats) (cf. Beek, 1989; Carson et al., 1994; Byblow et al., 1994, 1995; Roerdink, 2008; Roerdink et al., 2013). In this case an interpretation may be that f_c refers to an internal timing process (which can be generated by means of a non-linear oscillator), and the modulations are associated with the anchoring process (tuning into a temporal target).

Although we believe that rhythmic frequency modulation is shown to be an interesting technique in making syntheses of timed repetitive continuous movements, many aspects of our model should certainly undergo further development and change. New empirical investigations of how various timing tasks are reflected in movement trajectories and additional quantitative analysis of comparison between motion data and FM syntheses are

required to develop the model further. On the basis of the statement of Balasubramaniam et al., 2004, p.133: “The question of what kind of optimality principles are used by the CNS during trajectory formation in timed repetitive movements that satisfy constraints of accuracy and period stability is likely to be an important avenue for future research”, it would, moreover, be interesting to investigate to what extent aspects of frequency modulation, which in the present paper are shown to mirror various characteristic features of trajectories in timed repetitive movements, are also reflected in processes within the central nervous system. In our future research we hope to contribute to some of the development of our knowledge within these matters.

Acknowledgements

The author is grateful to the anonymous reviewers for valuable comments and suggestions, and to Andreas Bergsland, Department of Music, Norwegian University of Science and Technology, for help in the motion tracking of finger movements.

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