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Cancelling discrete and stopping ongoing rhythmic movements: Do they involve the same process of motor inhibition?

M. Hervault[a,b,*], R. Huys[a], C. Farrer[a], J.C. Buisson[b,c], P.G. Zanone[a,b]

[a] Centre de Recherche Cerveau et Cognition – UMR 5549 CNRS, Pavillon Baudot CHU Purpan, BP 25202 - 31052 Toulouse Cedex, France
[b] Université Toulouse 3 Paul Sabatier, 118 route de Narbonne, 31062 Toulouse Cedex 9, France
[c] Institut de Recherche en Informatique de Toulouse, 118 Route de Narbonne, 31062 Toulouse Cedex 9, France

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ABSTRACT

Motor inhibition is considered to be an important process of executive control and to be implicated in numerous activities in order to cancel prepared actions and, supposedly, to suppress ongoing ones. Usually, it is evaluated using a "stop-signal task" in which participants have to inhibit prepared discrete movements. However, it is unknown whether other movement types involve the same inhibition process. We therefore investigated whether the inhibition process for discrete movements is involved in stopping ongoing rhythmic movements as well.

Twenty healthy adults performed two counterbalanced tasks. The first task was used to estimate the stop-signal reaction time (SSRTd) needed to inhibit prepared discrete key-pressing movements. In the second task, participants drew graphic patterns on a tablet and had to stop the movement when a stop-signal occurred. We calculated the rhythmic stop signal-reaction time as the time needed to initiate stopping such ongoing rhythmic movement (SSRTr) and the same latency relative to the period of the rhythmic movement (*rel*SSRTr). We measured these delays under different movement frequencies and motor coordination conditions and further investigated whether they varied as a function of several parameters of the rhythmic movements (speed, mean and variance of the relative phase, and movement phase at several time events).

We found no correlation between inhibition measures in the two tasks. In contrast, generalized linear models showed a moderate yet significant influence of the motion parameters on the inhibition of ongoing rhythmic movements. We therefore conclude that the motor inhibition processes involved in cancelling prepared discrete movements and stopping ongoing rhythmic movements are dissimilar.

1. Introduction

Traditionally, the investigation of discrete and rhythmic movements control has been pursued from several perspectives using different tools and concepts (Buchanan, Park, Ryu, & Shea, 2003; Schaal, Sternad, Osu, & Kawato, 2004; Schmidt, 1975). Discrete movements are defined as movements between a succession of postures with zero velocity and acceleration, while continuous movements lack such recognizable endpoints and are typically considered as rhythmic if they constitute (periodic) repetitions of particular events (Hogan & Sternad, 2007).

Various authors argued discrete and rhythmic movements to be controlled by a similar process, that is, to be governed by a single primitive, whatever the task. Some authors held this primitive to be fundamentally discrete (Feldman, 1980), whereas other have

* Corresponding author at: CNRS CERCO UMR 5549, Pavillon Baudot CHU Purpan, BP 25202 - 31052 Toulouse Cedex, France.
E-mail address: mario.hervault@cnrs.fr (M. Hervault).

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argued that it is fundamentally rhythmic (Mottet & Bootsma, 1999). More recently, the literature appears to have converged on a consensus stating that rhythmic and discrete movements form two different classes (but see Daffertshofer, van Veen, Ton, & Huys, 2014). The standard procedure presented in movement science handbooks (e.g., Schmidt & Lee, 2005) is to distinguish rhythmic and discrete movements on the basis of observable kinematics following the methods pioneered by Brooks (1974). This distinction is consistent with inferences drawn from empirical behavioral studies (Buchanan et al., 2003) and theoretical work (Hogan & Sternad, 2007; Huys, Jirsa, Studenka, Rheaume, & Zelaznik, 2008). Accordingly, rhythmic movements do not consist of concatenated discrete movements, no more than discrete movements are truncated rhythmic movements.

Other research has shown differences in the neural structures associated with controlling discrete and rhythmic movement (Schaal et al., 2004; Spencer, Zelaznik, Diedrichsen, & Ivry, 2003). Such differences may be related to differing timing and movement initiation mechanisms (Huys, Studenka, Rheaume, Zelaznik, & Jirsa, 200b; Huys, Studenka, Zelaznik, & Jirsa, 2010). Taken together, these findings indicate that discrete and rhythmic movements might tap into distinct mechanisms of action control. If so, there is no a priori reason to expect that a single mechanism is involved in inhibiting discrete and ongoing rhythmic movements. At any rate, the existence of different control mechanisms in discrete and rhythmic movements does not preclude the possibility of the involvement of a (partially) similar inhibition process, operating, for instance, on a different level than those associated with movement generation. However, to our best knowledge, whether or not movement inhibition in discrete and rhythmic movements rely on the same process (es) has not been investigated yet.

Behavioral inhibition is generally conceived of as a core executive function involved in the control of attention, thought, emotion, and action (Bari & Robbins, 2013; Diamond, 2013; Miyake et al., 2000). As one of the most investigated aspects of action executive control, motor inhibition refers to the ability to cancel motor responses and planned actions. It allows people to flexibly adjust their behavior according to their changing goals. Everyday life readily illustrates the importance of motor inhibition, such as stopping oneself from crossing a street when a car comes around the corner or cancelling the reflex to grasp a hot pan falling from the stove. Indeed, inhibition deficits contribute to psychopathologies such as obsessive–compulsive disorder and attention deficit hyperactivity disorder (Chamberlain, Fineberg, Blackwell, Robbins, & Sahakian, 2006; Sergeant, 2005).

One of the simplest and most popular ways to investigate motor inhibition is by examining how people intentionally inhibit a planned movement in response to an external event. Typically, motor inhibition is evaluated using a stop-signal task in which people must inhibit discrete movements (Matzke, Verbruggen, & Logan, 2018, for a review). This task requires participants to cancel an already planned discrete movement whenever the go-signal is unpredictably followed by a visual or auditory stop-signal (Verbruggen & Logan, 2008).

According to the popular horse-race model (Logan & Cowan, 1984), successful inhibition in the stop-signal task relies on the outcome of a race between independent GO and STOP processes. Inhibitory control succeeds when the STOP process finishes the race before the GO process, whereas inhibition fails if the GO process reaches the response threshold first. However, one may question the degree to which this race model provides insight into underlying processes: After all, it is but a model that accounts statistically for the observed stopping times distributions (Schall, Palmeri, & Logan, 2017). Still, the mathematical model underlying the horse-race model provides a way to estimate the actual duration of the covert motor inhibition process, the stop-signal reaction time (SSRT). Hence, the stop-signal paradigm offers an estimate of the latency to stop planned discrete movements. The SSRT is often estimated to last about 200–300 ms and proves to be independent of whether the discrete movement is executed with the finger, the wrist or the arm (Brunamonti, Ferraina, & Paré, 2012). The estimation of the SSRT based on discrete movement cancellation has been important in studying differences in the ability to inhibit motor responses between clinical and control groups (Chamberlain et al., 2006; Lijffijt, Kenemans, Verbaten, & van Engeland, 2005), with development in childhood (Williams, Ponesse, Schachar, Logan, & Tannock, 1999), and between neurological patients and controls (Gauggel, Rieger, & Feghoff, 2004). Finally, the SSRT has also been instrumental in investigating the neurophysiology of motor inhibition (Bari & Robbins, 2013).

The stop-signal task was developed as a tool to evaluate a generic process of motor inhibition (Band & van Boxtel, 1999; Logan & Cowan, 1984). For an ongoing rhythmic movement, however, it makes little sense to propose a race between the GO and STOP processes because the movement is ongoing, invalidating the method as a means to evaluate motor inhibition. Consequently, but also for other reasons, movements other than discrete ones have been ignored in most literature on inhibition. Indeed, rhythmic movements, let alone the distinction between discrete and rhythmic movements, were totally absent of a recent special issue of *Philosophical Transactions of the Royal Society B* (2017, volume 372, issue 1718) devoted to movement suppression. Especially, the absence of the rhythmic movement case in the paper of Schall et al. (2017), reviewing the models of motor inhibition, reflects the consideration of reactive motor inhibition as a unitary process. By assumption, often implicit, the very same process would underlie inhibition of all kinds of movement.

However, some studies showing a distinction between motor inhibition forms call into question the claim of motor inhibition as a unitary construct. For instance, the anti-saccade task revealed different forms of saccade suppression (Coe & Munoz, 2017); Earlier research has reported that the motor cortex excitability is modulated in a phasic fashion by rhythmic wrist flexion/extension movements (Stinear & Byblow, 2002). The motor system would then make use of such phasic modulations when stopping an ongoing movement, so that it preferentially stops at specific points in the movement (and motor cortex excitability) cycle. Yet, such inhibition modulation is admittedly absent when preparing for a discrete movement. Therefore, while the existence of a generic mechanisms underlying motor inhibition is often assumed, it is still unclear whether the inhibition process evaluated by the stop-signal task is involved in stopping movements regardless of their type.

A few studies have explored the stopping of ongoing responses in continuous stop-signal tasks (Morein-Zamir & Meiran, 2003; Morein-Zamir et al., 2004, Morein-Zamir, Franks, Nagelkerke and Kingstone, 2006; Morein-Zamir, Nagelkerke, Chua, Franks, and Kingstone 2006). The authors asked participants to track a target moving on a screen with a mouse or by pressing a force sensor,

which allowed the participants to control the direction or speed of the continuous tracking, respectively. In the 2004 study (Morein-Zamir, Nagelkerke, Chua, Franks, & Kingstone, 2004), participants had to track a target, which rotated along an imaginary circle on the screen. The response cursor speed increased when the participants increased pressure on the force sensor (the cursor's direction was independent of the participants' actions). After a variable delay, a visual stop-signal (the target stopped moving) instructed participants to stop the ongoing response as fast as possible. The SSRT was defined as the moment when the pressure offset occurred in the response pressure profile. The authors found that the SSRT in the discrete stop-signal task and in the continuous tracking task were highly correlated ($r = 0.84$). This correlation was interpreted as an indicator of an overlap in the control processes of the prepared discrete responses and the ongoing continuous responses, supporting the claim that there exists a general mechanism for motor response inhibition. Yet, one may remark that in this tracking task, the participants did not control the target motion itself but only its speed through the force produced by a finger. The continuous target rotation on the screen was thus not generated by a continuous hand movement, since the only movement required from the participants was pressing or releasing a force sensor. The task thus required the application of a constant force and, arguably, more or less discrete corrections when the velocity controlled via force did not match the required target velocity, and not the generation of motion.

Other authors, however, have investigated stopping ongoing movements in (drawing) tasks in which both the movement path and the velocity profile were self-selected by the participants (Sosnik, Chaim, & Flash, 2015; Sosnik, Shemesh, & Abeles, 2007). The figural properties of the path generated after the stop-signal suggested that participants tended to complete their ongoing movements, or kinematic plans, before stopping, implying the existence of unstoppable motion units. Thus, executive control of action, such as movement planning, seems to influence the stopping performance of ongoing movements, which is not only affected by "low level" constraints. These studies, however, did access communalities (or their absence) between inhibiting and stopping movements of distinct types even though the continuous movements were not rhythmic. Therefore, it remains an open question whether stopping ongoing rhythmic movements and cancelling prepared discrete movements involve the same inhibition process.

Inspired by nonlinear dynamic systems theory, rhythmic movements have been conceptualized in terms of limit cycles, resulting in a smooth orbit in the phase space (velocity against position) (Kelso, 1995). In contrast, discrete movements are formalized as fixed points (Huys, Jirsa, et al., 2008; Jirsa & Kelso, 2005). Several movement patterns have been studied from a nonlinear dynamic perspective. In that regard, handwriting has been conceptualized in terms of the combined action of a pair of independent oscillators set in an orthogonal fashion (Hollerbach, 1981). Preferred shapes have been identified that correspond to specific and stable phase and amplitude relationships between the two oscillators (Athènes, Sallagoïty, Zanone, & Albaret, 2004). Like all rhythmic movements, graphic skills are governed by the dynamics of coupled oscillators that determine how they are generated and what their stability is. Moreover, one study showed that the stability of coordination involved in producing graphic shapes determines the switching time from one shape to another (Zanone & Athènes, 2013). By extension, we hypothesize that coordinative stability also modulates the effectiveness of stopping the production of graphic shapes.

To sum up, executive control of action, and particularly motor inhibition, has mainly been investigated using the stop-signal paradigm in which participants have to cancel prepared discrete movements. This paradigm is deemed to evaluate a general motor inhibition process. Yet, a few studies suggest that prepared discrete movements and ongoing rhythmic movement are not controlled by the same inhibitory mechanisms. In the present study, we asked participants to react to a stop-signal during a rhythmic hand movement of writing stable shapes. We aimed to compare SSRTr measured in stopping ongoing rhythmic movements and SSRTd estimated in cancelling prepared discrete movements in the stop-signal task. We tested whether stopping both movement types shared a common motor inhibition mechanism by examining whether inhibition latency was correlated across the two tasks. In addition, we further examined whether rhythmic movement parameters such as velocity and coordination pattern had an influence on the stopping performance.

2. Method

2.1. Participants

Twenty graduate students (12 males; 8 females) volunteered in the experiment (mean age 26 ± 4 (SD) years). All participants were healthy, right-handed and had normal or corrected-to-normal vision. Participants provided sociodemographic characteristics and written informed consent in accordance with the Helsinki Declaration.

2.2. Apparatus and stimuli

In the discrete movement task, participants were seated at a viewing distance of 60 cm from a computer screen (1920 × 1080-pixel resolution, 60 Hz refresh rate). They looked at a fixation sign ("+") and placed their right and left index fingers over the response keys fixed to the table in front of them. The primary-task stimuli were a square and a circle. The fixation sign and stimuli were presented in the center of the screen, in white on a black background. Occasionally, an auditory stop-signal (750 Hz, duration: 75 ms) was presented shortly after the stimulus onset in the primary task. The experiment was run using STOP-IT, a Windows executable software for the stop-signal paradigm (Verbruggen, Logan, & Stevens, 2008).

In the rhythmic movement task, participants were seated in front of a graphic tablet (WACOM Cintiq 15X, 1280 × 800-pixel resolution). Graphic pattern videos were displayed on the tablet screen using VLC software (version 2.1.5) indicating which pattern had to be produced and at what movement frequency. During the task, participants drew the proposed graphic patterns on the digitizing screen. As soon as the stylus touched the tablet, the x and y coordinates of the performed motions were digitized at a

sampling frequency of 143 Hz. After a variable delay, the screen briefly turned yellow to indicate to the participants to abort their movements. The program controlling the tablet was custom made.

2.3. Procedure

Participants completed the two tasks in a single one-hour session (task order counterbalanced).

2.3.1. Discrete movement task (stop-signal task)

The primary task was a two-choice reaction time task. When a circle appeared, participants were instructed to press the left response button with the left index finger, and when it was a square, they were told to press the right response button with the right index finger. On 75% of the trials (GO trials) only this stimulus was presented, and the participants had to respond to the stimulus as fast and accurately as they could. On 25% of the trials (STOP trials), the stimulus was followed by an (secondary-task) auditory stop-signal, which indicated to the participants that they had to cancel their movement.

The experiment consisted of a practice phase of 32 trials and an experimental phase of three blocks of 64 trials each. Each trial started with the presentation of the fixation sign, which was replaced by the stimulus after 250 ms. The stimulus remained on the screen until the participants responded, or until 1250 ms had elapsed. The inter-stimulus interval was 2000 ms and was independent of reaction time. On STOP trials, an auditory stop-signal was presented after a variable delay (SOA; stimulus onset asynchrony). The SOA, initially set to 250 ms, was dynamically adjusted in 50 ms increments to achieve a probability of responding [*p(respond|signal)*] of 0.5: after successful stops the SOA was prolonged; after failed stops it was shortened.

Between blocks, participants received information about their performance in the previous block: the number of incorrect responses on GO trials, the number of none-responses on GO trials, the mean reaction time on GO trials, and the percentage of correctly suppressed movements on STOP trials.

2.3.2. Rhythmic movement task (drawing task)

Following 16 training trials, the participants completed 6 counterbalanced conditions in which they performed 5 blocks of 10 trials. Each block began with the presentation of a graphic pattern video. Pattern shapes were constructed by combining the motion of two periodic signals, one for each direction (i.e., x [horizontal] and y [vertical]) according to:

$$x(t) = A \bullet \cos(\omega \bullet t)$$

$$y(t) = A \bullet \cos(\omega \bullet t + \varphi),$$

where A is the oscillation amplitude, ω the angular frequency ($\omega = 2\hat{A}\cdot\pi\bullet F$), and φ the relative phase between the two signals. Variations of the relative phase φ with the same oscillators' amplitude produce elliptic shapes (Fig. 1). These variations gave rise to two shapes that were displayed on the screen in the different conditions: a line and an ellipse with 0° and 45° relative phase, respectively. Both shapes were presented such that their main diagonal had a 45° angle with the horizontal. These shapes are known to correspond to stable and preferred coordination pattern in handwriting (Athènes et al., 2004). Participants watched the pattern as long as they needed to "get" the shape and the frequency of the pattern. They then executed one block of 10 trials to trace the same graphic pattern on the tablet. During the trials, the videos were no longer visible. On each trial, a visual stop-signal (consisting of the screen turning yellow) appeared randomly between 4000 and 8000 ms. The instruction was to stop the movement as fast as possible and to always maintain contact between the stylus and the writing surface throughout a trial. Six conditions were obtained by displaying the two different shapes (defined by the relative phases between the horizontal and the vertical signals) at three different frequencies, namely 0.50 Hz, 1.75 Hz, and 3.00 Hz.

2.4. Dependent measures

Data analyses were performed using Matlab™ software (Mathworks 2013).

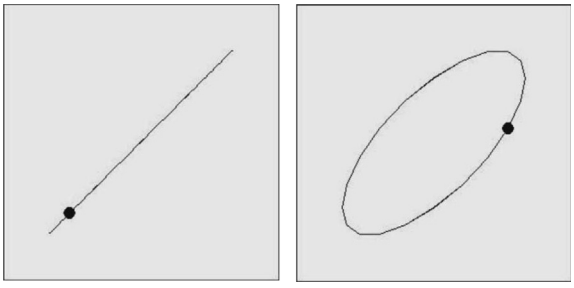

Fig. 1. Snapshots of the graphic shapes with a 0° (left panel) and 45° (right panel) phase difference between the oscillations in the horizontal and vertical directions. Each shape was presented with the dot rhythmically moving at 0.5 Hz, 1.75 Hz and 3 Hz.

2.4.1. Discrete movement task (stop-signal task)

For each block of each participant, mean Go-RT was calculated as the mean reaction time measured in the GO trials, and the mean SOA was calculated across STOP trials. Then, the discrete stop signal reaction time (SSRTd) was computed using the mean method, that is, by subtracting the observed mean SOA on STOP trials from the observed mean Go-RT on GO trials (Logan, 1994). SSRTd could be estimated for all participants as *p(respond|signal)* did not differ significantly from 0.5.

Fs-RT was also computed as the mean reaction time measured in failed STOP trials.

2.4.2. Rhythmic movement task (drawing task)

Time series for x and y on each trial were oscillatory. They were mean-centered and normalized via division through their maximum absolute amplitude, detrended, and low-pass filtered using a second order dual-pass Butterworth filter with a cutoff frequency of 12 Hz.

Next, we defined four 'rhythmic' inhibition values for each trial: Stop Time, Stop Time relative to the movement period (*rel*Stop Time*)*, stop-signal reaction time (SSRTr), and relative stop-signal reaction time (*rel*SSRTr). Stop time was the time from the stop signal onset to the movement stop of the participant. Movement stop was defined as the first moment in which the speed of the movement ($speed = \sqrt{\dot{x}^2 + \dot{y}^2}$) was inferior to 5% of the trials' maximum speed and remained below that value for minimally 100 ms. *rel*Stop Time consisted of the stopping time divided by the mean period of the trial's rhythmic movement. SSRTr was measured as the latency from stop signal onset to the onset of the response adjustment, that is, movement deviation relative to (visually) unperturbed movements. In order to identify movement deviations (relative to the pre-stop signal movements) we applied three criteria defined in the movement's phase space (for the horizontal and vertical direction separately). These criteria were based on a sample's (1) phase space position (*i*,*j*), and its corresponding velocity vector's (2) angle and (3) magnitude (norm). In detail, we first determined the movements' 'normal' features per condition but across trials. To that aim, for each trial we selected the last two cycles prior to the signal-to-stop occurrence, and calculated the 2D phase space probability distribution *P(x,dx/dt)*. Thereto, the phase space was divided in 20 × 20 bins. Summing these distributions over trials, we obtained a single 20 × 20 probability distribution containing for each bin indicating the number of times the bin had been visited per condition. Next, for each sample found in a given bin, we calculated the velocity vector and determined its magnitude (norm). For each bin, we then calculated the angles between all velocity-vector pairs (where each velocity vector corresponds to a single visit of that bin). In order to obtain across trial (but per condition) statistics, we then calculated the mean and standard deviation of the vectors' angles and magnitudes.

As a next step, for each trial, and from the moment of the stop-signal occurrence onwards, we evaluated whether the given sample was found in a part of the phase space it 'normally' visited (criterion 1). In particular, we identified the bin in which the movement (sample) was "currently" positioned, how often that bin had been visited in the pre-stop signal (i.e., normal) movements, and classified the sample as deviating whenever the following criterion held: $P(i,j)/\mathrm{sum}(P) < 0.5/N\hat{}2$ (with $N = 20$ [bin size]). If this was the case, criterion 1 was met. Whenever this was not the case, we determined the angle between the sample's velocity vector and the mean velocity vector for that bin. If that angle deviated more than three (across-trial) standard deviations from the across-trial mean, criterion 2 was met. Whenever this was not the case, we determined the sample's velocity vector magnitude. If that magnitude deviated more than three standard deviations from the mean for that bin, criterion 3 was met. Whenever any of these criteria were met for three consecutive samples, the moment of movement deviation was taken as the first of these three samples. All movement deviations were visually checked (Fig. 2). *rel*SSRTr was then calculated as the SSRTr divided by the mean period of the concerned trial.

Four movement's parameters were calculated for each trial. Movement speed was calculated as the speed of the movement at the moment the stop signal occurred. Mean relative phase φ between the x and y oscillations was computed across each trial. Using circular statistics (Mardia & Jupp, 1999), the relative phase variance (*var*RP) was also computed for each trial to assess the stability of the coordination between the two oscillators. Based on the movement trajectory in phase space we extracted the phase of the movement as different events (stop-signal occurrence, movement deviation, and movement stop) occurred. For each event, the extent of the phase concentration across trials was quantified using the inter-trials phase clustering (ITPC) (Busch, Dubois, & VanRullen, 2009):

$$ITPC = \frac{1}{n}\sum_{n=1} e^{i(\phi 2\pi)}$$

with ϕ the phase on the trajectory. As a phase locking factor, ITPC takes value between 0 and 1. A value of 0 represents absence of synchronization across trials between phase space trajectory and time-locking events, and a value of 1 indicates perfect synchronization.

3. Results

Statistical analyses were performed using R software (version 3.4.4).

3.1. Inhibition measures of discrete and rhythmic movements

In the stop-signal task, mean Go-RT (M = 444 ms, SD = 78.0 ms) was significantly longer than mean Fs-RT (M = 418 ms, SD = 53.9 ms) indicating the validity of the race model between GO and STOP processes ($t(19) = 3.63, p < .01$). To compute SSRTd,

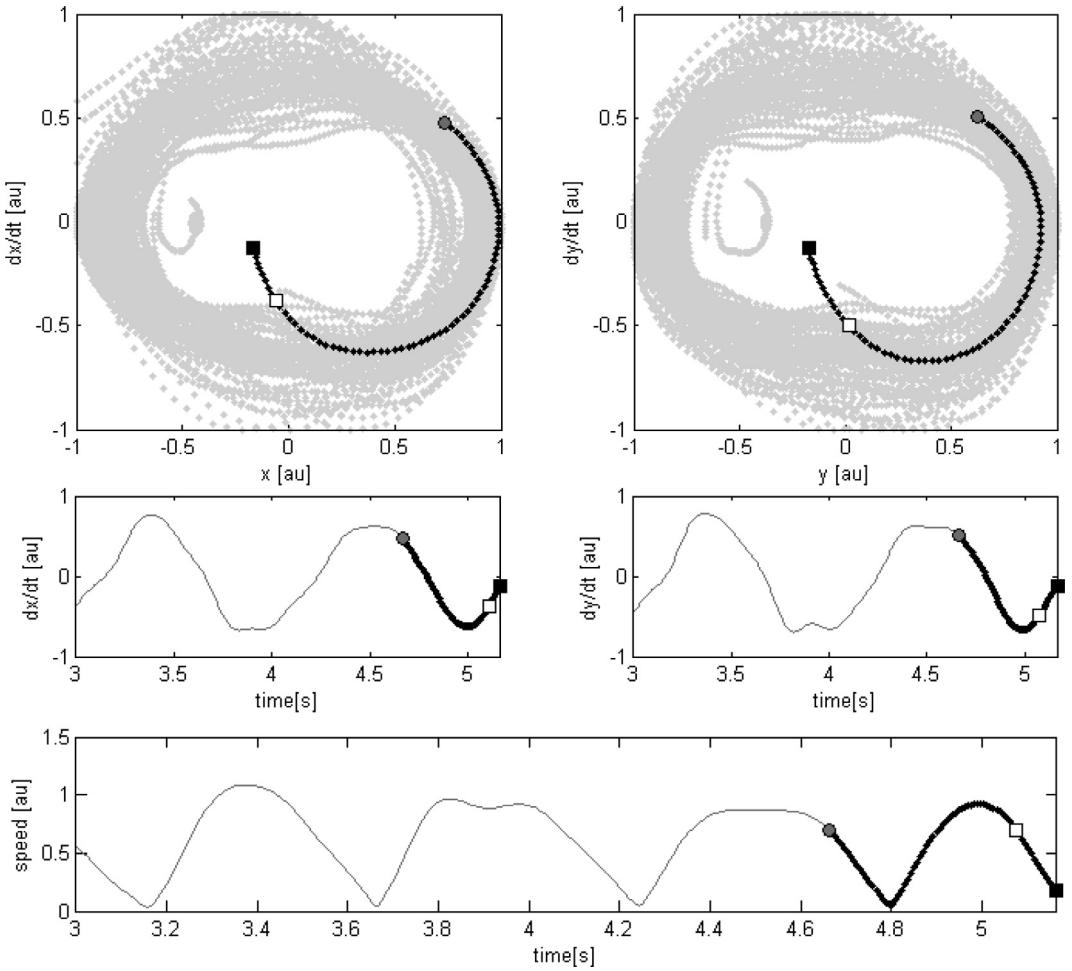

Fig. 2. A trial with a movement deviation (RP = 0°; Frequency = 0.5 Hz). Upper panel: Normalized phase space of *x* and *y* component (au: arbitrary unit of normalized data; in grey: trajectories of the 50 trials of this condition; ●: stop signal; ■: movement stop; □: movement deviation); Middle panel: Velocity profile on *x* and *y* components; Lower panel: Speed profile.

average SOA for participants was 176 ms (SD = 93.8 ms).

Across participants, SSRTd (M = 266 ms, SD = 38.0 ms) and SSRTr (M = 297 ms, SD = 31 ms) were significantly different ($t(19) = 3.06$, $p < .01$). Thus, the inhibition latency for ongoing rhythmic movements was on average 31 ms longer than for prepared discrete movements (CI: 9.9 ms – 52 ms).

Pearson correlations were computed between all inhibition measures (Table 1). Across participants, the correlation of main interest, that is, between SSRTd and SSRTr, turned out to be non-significant. Thus, a participant who was fast at inhibiting a prepared discrete movement was not systematically fast at inhibiting an ongoing rhythmic movement. However, the discrete Go-RT correlated positively with the inhibition measures of rhythmic movements SSRTr ($r = 0.44$, $p < .05$) and Stop Time ($r = 0.52$, $p < .05$). For the drawing task, we further found strong correlations between the temporal measures of inhibition (Stop Time and SSRTr, $r = 0.92$, $p < .001$) and the measures relative to the period of the oscillation (*rel*Stop Time and *rel*SSRTr, $r = 0.91$, $p < .001$). Note, however, that the Stop Time includes the SSRTr, which to some degree surely explains these later correlations and underline the importance of

Table 1
Pearson correlation matrix of the dependent variables of the two tasks. *p < .05 **p < .01 ***p < .001.

	Go-RT	SSRTd	SSRTr	relSSRTr	Stop Time	relStop Time
Go-RT	1	−0.19	0.44*	0.31	0.52*	0.26
SSRTd		1	0.14	-0.29	0.05	-0.41*
SSRTr			1	0.54*	0.92***	0.21
relSSRTr				1	0.71***	0.91***
Stop Time					1	0.45*
relStop Time						1

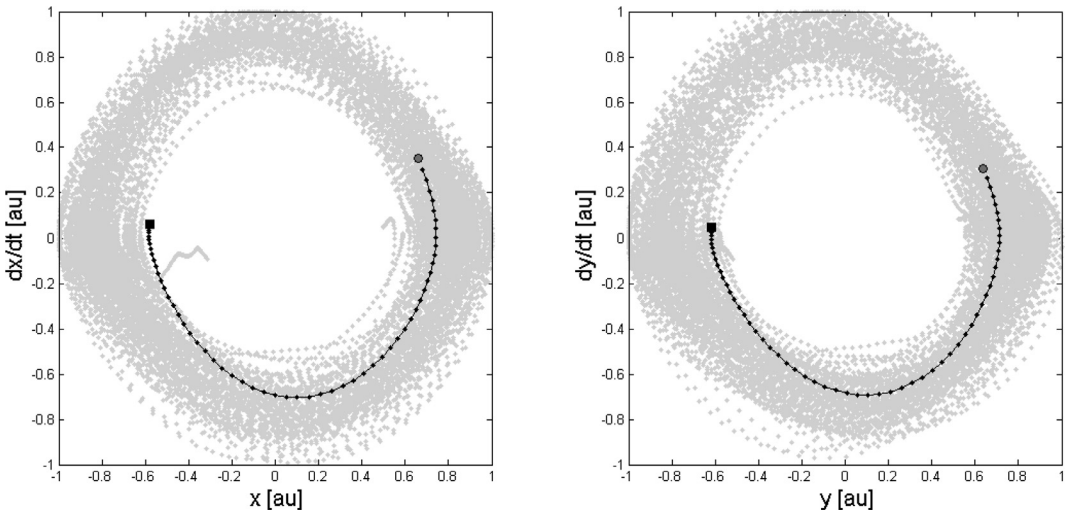

Fig. 3. A trial without movement deviation (RP = 0°; Frequency = 1.75 Hz). Normalized phase space of *x* and *y* components showing no movement deviation between the stop signal (●) and the movement stop (■).

a fast inhibition process in the final stopping performance.

Surprisingly, SSRTr could not be defined for all trials. Some ongoing rhythmic movements were stopped without the movement deviating from its trajectory prior to the stop-signal in the phase space. This observation concerned 23.8% of the trials in the study, mainly in conditions 0° PR − 0.5 Hz, 45° PR − 0.5 Hz and 0° PR – 1.75 Hz (which gather 80.1% of those no deviation trials). In such trials, Stop Time was defined but the movement deviation, and thus the SSRTr, were not (Fig. 3). Furthermore, Stop Time was significantly different between trials without deviation and trials with deviation ($t(667.9) = 23.9$, $p < .001$). Stop Time was 113.1 ms shorter (CI: 103.1 ms – 123.2 ms) in trials without movement deviation compared to trials with deviation. *rel*Stop Time was also 0.52 shorter (CI: 0.45 – 0.96) in trials without deviation ($t(1128.4) = 29.4$, $p < .001$).

3.2. Rhythmic movement parameters

The rhythmic movement were produced with mean frequencies of 0.52 Hz (SD = 0.15 Hz), 1.99 Hz (SD = 0.37 Hz), and 3.31 Hz (SD = 0.60 Hz), for the 0.50 Hz, 1.75 Hz, and 3.0 0 Hz patterns, respectively. Thus, while the required movement frequencies were not exactly matched, the produced frequencies were clearly different in the three frequency conditions and fell within 15% of those required. Two pattern conditions were used, with a 0° and 45° relative phase between the horizontal and vertical sinusoids. Participants performed drawing as requested with on average a relative phase of 1° (SD = 1.2°) and 44.9° (SD = 8.2°).

Mean values of rhythmic movement inhibition are shown in Table 2. To explore the relations between movement parameters and rhythmic movement inhibition measures, generalized linear models with Gamma or Gaussian distribution were computed. Model's goodness of fit was assessed using McFadden's pseudo-R2. Wald Chi-squared tests were subsequently conducted to test whether movement parameters had a significant effect on inhibition measures.

In the drawing task, inhibition measures were different across the conditions. However, the differences were not remarkable

Table 2
Mean (SE) values of rhythmic movement measures for all the participants in the different conditions of the drawing task.

Frequency condition (Hz)	0.50		1.75		3.00	
Relative phase condition (°)	0	45	0	45	0	45
SSRTr (ms)	207 (4.59)	225 (3.88)	261 (3.86)	278 (3.10)	298 (2.88)	304 (3.01)
relSSRTr	0.14 (2.0 e−3)	0.14 (2.2 e−3)	0.59 (7.2 e−3)	0.60 (6.0 e−3)	1.07 (10.2 e−3)	1.00 (8.8 e−3)
Stop Time(ms)	381 (3.98)	414 (3.19)	410 (3.19)	438 (2.71)	504 (2.65)	497 (2.77)
relStop Time	0.20 (2.2 e−3)	0.20 (2.4 e−3)	0.81 (8.7 e−3)	0.89 (7.9 e−3)	1.75 (16.5 e−3)	1.59 (12.1 e−3)
varRP (°)	0.26 e−2 (0.27 e−2)	3.11 e−2 (1.89 e−2)	0.25 e−2 (0.29 e−2)	1.77 e−2 (1.63 e−2)	0.17 e−2 (0.23 e−2)	1.57 e−2 (1.19 e−2)
Speed (a.u.)	0.49 (0.07)	0.39 (0.11)	2.14 (0.10)	2.24 (0.24)	3.13 (0.39)	3.56 (0.24)

between the 0° and 45° relative phases; the main effect was due to the three 0.50 Hz, 1.75 Hz and 3.00 Hz frequency conditions. Thus, an increase in movement frequency induced an increase of inhibition latencies: Stop Time ($\chi^2 = 1140.16$, df = 2, $p < .001$; pseudo $R^2 = 0.16$), *rel*StopTime ($\chi^2 = 17724$, df = 2, $p < .001$; pseudo $R^2 = 0.85$), SSRTr ($\chi^2 = 509.03$, df = 2, $p < .001$; pseudo $R^2 = 0.05$) and *rel*SSRTr ($\chi^2 = 10487$, df = 2, $p < .001$; pseudo $R^2 = 0.83$). Along this line, movement speed (i.e., the instantaneous speed at the moment of stop signal onset) also had a significant influence on Stop Time ($\chi^2 = 880.35$, df = 1, $p < .001$; pseudo $R^2 = 0.13$), *rel*Stop Time ($\chi^2 = 8032.8$, df = 1, $p < .001$; pseudo $R^2 = 0.60$), SSRTr ($\chi^2 = 558.73$, df = 1, $p < .001$; pseudo $R^2 = 0.09$) and *rel*SSRTr ($\chi^2 = 5076.6$, df = 1, $p < .001$; pseudo $R^2 = 0.55$). This result indicates that the faster the movement at the moment of the stop-signal occurrence, the longer the time to start deviating (if so) and stop the movement.

As for the rhythmic movement coordination, the mean produced relative phase did not show a significant effect on the inhibition measures. However, the stability of the coordination did, even though the fit was weak: the relative phase variance had a significant effect on *rel*SSRTr ($\chi^2 = 352.58$, df = 1, $p < .001$; pseudo $R^2 = 0.06$) and *rel*Stop Time ($\chi^2 = 200.64$, df = 1, $p < .001$; pseudo $R^2 = 0.03$), indicating that motor inhibition was facilitated for stable movement coordination compared to less stable one.

Based on the phase space trajectory, the phase at which the three events occurred (stop-signal, movement deviation, and movement stop) did not show an influence on inhibition latencies. Thus, the participants stopped their movements in the same way whatever the phases of these events. Moreover, equally for the six experimental conditions, neither the stop-signal phase nor the movement deviation phase revealed signs of phase clustering (both ITPC < 0.1). Thus, the time-locked events were approximately randomly distributed on phase space trajectory across trials.

However, the phase at which the stop-signal occurred appeared to influence detection of any movement deviation before the actual rhythmic movement's stop. In order to evaluate this dependence, we computed two distributions of the stop-signal phase, for trials with deviation and trials without deviation. A two sample Kolmogorov-Smirnov test showed a significant difference between the two distributions ($D = 0.0454$, $p < .05$), even though difficult to interpret. To evaluate the dissimilarity between the two distributions, the relative entropy was computed using the Kullback–Leibler divergence and showed 6% dissimilarity ($D = 0.0603$).

4. Discussion

4.1. Different kinds of inhibition in discrete and rhythmic movements

We used the stop-signal task and a drawing task to test whether cancelling prepared discrete movements and stopping ongoing rhythmic movements shared the same motor inhibition process. Discrete movements latencies of initiation and inhibition were similar to those typically reported in the stop-signal task literature (Logan & Cowan, 1984; Verbruggen & Logan, 2008). Moreover, the found difference between SSRTd and SSRTr was consistent with previous research showing a longer inhibition latency to stop ongoing action compared to a prepared discrete response (Morein-Zamir et al., 2004). However, our finding that no correlation exists between the inhibition latencies in the two tasks contrasts with previous studies involving a kinematic task (Bachorowski & Newman, 1985; Morein-Zamir et al., 2004). Such difference might be due to the differences in task constraints between our drawing task and the tracking tasks used by Morein-Zamir et al. (2004, 2006) (see also above). In that regard, while it is uncertain what type of (dynamical) movement organization underlies tracking (cf. Huys, Jirsa, et al., 2008; Huys, Perdikis, & Jirsa, 2014), it can be excluded that the tracking in the tasks used by Morein-Zamir and colleagues are amenable to a description in terms of limit cycles. That is, they were altogether different from the rhythmic movements investigated in the present study, involving an actual 2D movement and not mere pressure variations. Thus, our result claims for a dissociation in the inhibition process depending on the sole discrete vs. rhythmic character of the movement to stop.

Inhibitory control is not a unitary construct but comprises different kinds of inhibition, including motor inhibition (Nigg, 2000). In fact, differences as well as correlations between various forms of inhibition have been reported (Friedman & Miyake, 2004). In particular, motor inhibition is deemed to share common mechanisms with other forms of inhibition (Verbruggen, Liefooghe and Vandierendonck, 2004, 2006). However, we suggest that motor inhibition, presumed to form a generic process in most of the studies in cognitive (neuro)psychology, is not a unitary construct but implies (at least, partially) separate processes according to the discrete or rhythmic character of the to-be-stopped movement. If we consider that discrete and rhythmic movements are not generated and controlled by the same mechanisms (Huys et al., 2014; Schaal et al., 2004; Spencer et al., 2003), there is no a priori reason that a single process be implied in their inhibition. Moreover, depending of the movement frequency and, to a small degree, of its phase at the stop-signal occurrence, different mechanisms could be involved in stopping ongoing rhythmic movements. Indeed, a majority of the stopped rhythmic movements showed a clear deviation in phase space relative to their (previous) ongoing movement, but some movements were stopped without such deviation. The significantly shorter Stop Time in the former trials suggests that the reason is not a failure of the detection algorithm.

Neuroimaging studies have explored the cerebral areas involved in motor inhibition using a stop-signal task (see Aron, 2011, for a review). A fronto-basal-ganglia network, including right inferior frontal cortex (rIFC) and pre-supplementary motor area (pre-SMA), was associated with the motor inhibition of prepared discrete movements. To our knowledge, no study has explored the brain areas associated with rhythmic movements inhibition. However, some studies indicated that rhythmic and discrete upper-limb movements recruit, at least partially, distinct neural circuitries. In particular, Schaal et al. (2004) found that rhythmic wrist movements recruit a smaller cortical network than discrete movements. Our suggestion of different kinds of motor inhibition processes is in line with such findings.

4.2. The influence of movement frequency and stability on ongoing rhythmic movements inhibition

Movement frequency had a main effect on stopping performance in the rhythmic drawing task. SSRTr increased when the movement frequency was higher. On average, about half a period was required to inhibit a 1.75 Hz movement and an entire period to inhibit a 3.00 Hz movement. This finding contrasts an earlier one that reported that the speed of a to-be tracked the target influenced tracking performance but not SSRT (Morein-Zamir & Meiran, 2003). Indeed, our results showed a significant effect of speed on inhibiting ongoing rhythmic movements. It is unclear, however, whether this effect can be ascribed to inertia or if it points towards a differential processing of the signal to stop and/or first inhibition phases. At any rate, the weak fit of the used model does not allow to precisely assess the link between movement speed and absolute value of SSRTr.

In the drawing task, movement stability was defined as the variability of the relative phase between x and y oscillations and showed a significant effect on stopping performance. If we consider that graphic patterns of 0° and 45° relative phase correspond to stable coordination patterns (Athènes et al., 2004), the weak model fit between this variability and inhibition measures can be readily understood: the less stable condition, 45° relative phase, might still be too stable to strongly affect coordination and potentially stopping performance. Notwithstanding, this effect suggests that movement stability has an influence on rhythmic movement inhibition. This assumption could be further investigated using a larger panel of relative phase conditions: Less-stable graphic patterns should increase the stability effect on stopping performance. In this line of thought, it was found that movement stability influences switching time in a double-task paradigm associating a bimanual coordination task and a reaction time task (Zanone, Monno, Temprado, & Laurent, 2001).

Although the phasic modulation of rhythmic movements has previously been shown to influence inhibitory activity in the motor cortex (Stinear & Byblow, 2002), the stop-signal phase and deviation phase did not directly influence the stopping performance in our experiment, suggesting that participants can stop a rhythmic movement independent of their location on the phase space trajectory. However, the found difference in stop-signal phase between trials with deviation and trials without deviation suggests that the two types of inhibiting rhythmic movements may have some phase dependency. Note that this finding concerned mostly low frequency (0.5 Hz) movement which may not be rhythmic in the strict sense of being ascribed to a limit cycle dynamics.

Another question is raised by the found correlation between Go-RT measured in the stop-signal task and SSRTr calculated in the drawing task. Some studies have indicated that response stopping, like response initiation, is influenced by stimulus–response properties such as compatibility (Morein-Zamir, Nagelkerke, et al., 2006). These findings suggested that stopping is governed by constraints similar to those of other reactive behaviors. Our results showing no correlation between SSRTd and SSRTr, but significant correlation between Go-RT and SSRTr could also be understood as the involvement of partially distinct motor inhibition processes in the two tasks, associated with a partially shared mechanism of reaction to a signal. This hypothesis is in accordance with previous studies showing that there is an overlap in the processing stages of voluntary movement initiation and suppression at a cortical level (Stinear, Coxon, & Byblow, 2009). Further research should evaluate the possible contribution of a general reactive mechanism in executive processes of action control, such as movement initiation and movement inhibition.

4.3. Perspectives

The involvement of the inhibition process in stopping a rhythmic ongoing movement could be investigated further using ERP derived from scalp EEG. Indeed, electrophysiological responses evoked by stop trials of discrete movements have often been interpreted as indicators of an inhibitory process. The right fronto-lateral N2 and the the fronto-central *P*3 waves are often reported as a correlate of successful response inhibition in the stop-signal task (Huster, Enriquez-Geppert, Lavallee, Falkenstein, & Herrmann, 2013; Wessel & Aron, 2015). Thus, differences in onsets or amplitudes of ERPs could give indications on the community/dissociation of the motor inhibition processes involved in stopping discrete and rhythmic movement.

Another strategy to study the purported dissociation between inhibition processes in different movements could be to recruit participants with executive deficits. Typically, a lack of inhibitory control proved to be a core deficit in people with attention deficit and hyperactivity disorder (ADHD). Indeed, stop-signal task completion by these patients showed that SSRT was longer than Go-RT relative to controls (Bekker et al., 2005). However, it is not clear whether this deficit in motor inhibition of prepared responses percolates to inhibition of ongoing responses. Using the tracking tasks of Morein-Zamir et al. (2003, 2006), no ADHD effect on SSRT was found in one study (Scheres et al., 2004) while a significant ADHD effect was found in another (Morein-Zamir, Hommersen, Johnston, & Kingstone, 2008). If ADHD people showed a deficit in cancelling prepared discrete movements but not in stopping ongoing rhythmic movements, this would support the claim of a distinction between the two processes.

Moreover, given the temporal variability in ADHD behavior, differences in stop-signal task performance cannot be attributed solely to inhibition deficits in patients (Castellanos, Sonuga-Barke, Milham, & Tannock, 2006; Lijffijt et al., 2005). The estimation of SSRTd using stopping prepared discrete movements does not allow considering this intra-individual variability. However, measured SSRTr in stopping ongoing rhythmic movements can be used to ask if response inhibition is longer and/or more variable in ADHD (Morein-Zamir et al., 2008).

5. Conclusion

The present study pointed out the differences in the inhibition latencies required to suppress the movement in the stop-signal task and a drawing task. This supports the hypothesis that (partially) different processes are involved in cancelling prepared discrete movements and stopping ongoing rhythmic movements. Thus, motor inhibition might not be a unitary construct but could require

distinct mechanisms depending on the type of the movement to inhibit. The relative contribution of a shared mechanism of inhibition and some specific movement dependent processes should be further explored. Clinical or neurophysiological experiments could investigate the nature of the dissociation/overlap between the mechanisms of motor inhibition involved in different kinds of movement control.

Moreover, as rhythmic movement parameters, namely movement frequency and stability, seemed to modify stopping performance, further experiments manipulating task constraints are needed to explore theses effects.

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