nature neuroscience

Rhythmic arm movement is not discrete

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Rhythmic movements, such as walking, chewing or scratching, are phylogenetically old motor behaviors found in many organisms, ranging from insects to primates. In contrast, discrete movements, such as reaching, grasping or kicking, are behaviors that have reached sophistication primarily in younger species, particularly primates. Neurophysiological and computational research on arm motor control has focused almost exclusively on discrete movements, essentially assuming similar neural circuitry for rhythmic tasks. In contrast, many behavioral studies have focused on rhythmic models, subsuming discrete movement as a special case. Here, using a human functional neuroimaging experiment, we show that in addition to areas activated in rhythmic movement, discrete movement involves several higher cortical planning areas, even when both movement conditions are confined to the same single wrist joint. These results provide neuroscientific evidence that rhythmic arm movement cannot be part of a more general discrete movement system and may require separate neurophysiological and theoretical treatment.

From the viewpoint of vertebrate neurobiology, rhythmic movement generation is primarily associated with pattern-generator circuits in the spinal cord and the brainstem. However, it has been difficult to locate elements of such circuits in higher vertebrates because of the complexity of these nervous structures and their additional modulation by higher brain centers in the mature system[1]. In humans, studies of the development of infant locomotion and microstimulation in patients with spinal cord injury have provided some behavioral evidence for pattern generators, again assumed to be on the spinal or brainstem level[2–4]. Owing to the ubiquitous presence of rhythmic movements, a large proportion of behavioral research in motor control uses the rhythmic pattern generation metaphor as a guiding model[5–7].

Conversely, neuroscience research into primate arm movements has almost exclusively been conducted on discrete and visually guided reaching[8–11], seemingly under the assumption that rhythmic arm movements are a special case in which the neural-reaching circuit is used repeatedly. Several prominent computational models of arm movement are based on discrete strokes between a start and an end point[12,13] or, to generate more complex trajectories, a start and an end point with intermediate via points[14,15], using either extrinsic (for example, Cartesian) or intrinsic (for example, joint or muscle space) coordinates to plan and execute the trajectory between these landmarks[16]. From this viewpoint, rhythmic arm movement is a sequence of movements between recurrent via points[11,17–19].

However, recent behavioral evidence has created some doubt as to whether this subsumption of rhythmic arm movement by discrete movement is appropriate. For instance, a series of studies[20–22] have demonstrated that certain kinematic features of the hand trajectory in rhythmic arm movement, previously interpreted as signs of segmented movement generation, can actually be accounted for by oscillator-based and/or optimally smooth movement generation, that is, without the need for any segmentation. Experiments that tested the possibility of superposition of rhythmic and discrete patterns in arm movements also concluded that rhythmic and discrete movement might be two different movement regimes[23–25]. Similar conclusions were obtained in a Fitts movement paradigm: in rhythmic performance, significantly higher movement speed can be tolerated at the same level of goal accuracy as in discrete movement[26]. Some initial computational models have been suggested to make the difference between rhythmic and discrete movement explicit and to explore the general value of such theories in computational neuroscience and behavioral experiments[23,27–29].

To examine the difference between rhythmic and discrete movement at a neural level, we compared brain activity in rhythmic and discrete wrist movements in a 4-Tesla human functional neuroimaging (fMRI) experiment. We predicted that if rhythmic movements were just a sequence of discrete movements, rhythmic activity (RA) should be the same as or more than discrete activity (DA), that is, RA $\supseteq$ DA, owing to the extra demands of sequencing. In contrast, if discrete movements were a special case of rhythmic movement—for example, an aborted limit cycle—we would expect RA $\subseteq$ DA, owing to the extra demands of terminating an ongoing movement. If discrete activity and rhythmic activity were different units of action, they should overlap only to some extent and each of them should have distinct sites of activity.

The task for participants was to perform single-joint wrist flexion-extension movements inside the scanner (**Fig. 1a**). In Experiment 1, a visual signal instructed participants to perform one of three movement conditions: 'Rhythmic', 'Discrete' or 'Rest', each lasting for 30 s (typical wrist trajectories from these movement conditions are shown in **Fig. 1b**). The 'Rhythmic' condition required continuous wrist oscillations at a self-chosen comfortable frequency. The 'Discrete' movement condition involved a moderately fast flexion-extension movement; if the start position was a flexed wrist posture, the wrist

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Published online 26 September 2004; doi:10.1038/mm1322

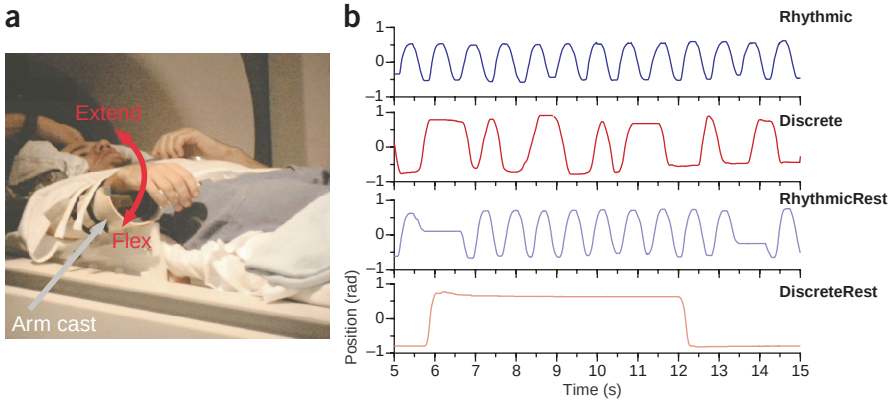

Figure 1 Experimental setup and conditions. (**a**) View of one participant outside of the scanner, showing the arm cast and direction of the wrist movements. (**b**) Angular position traces of wrist flexion-extension movement of one representative participant. For summary statistics of kinematic movement data, see **Table 1**.

was extended; if the start posture was an extended wrist posture, the wrist was flexed. Importantly, the movement had to come to a clear stop between two movements. The onset times for discrete movements were self-chosen at random intervals by each participant after some practice outside of the scanner. The 'Rest' condition required no movement. In a 6-min session, each condition was presented four times in a randomized fashion. Eleven participants performed two such sessions each. Experiment 2 was similar to Experiment 1, but four movement conditions were required: 'Rhythmic', 'RhythmicRest', 'DiscreteRest', and 'Rest'. Whereas 'Rhythmic' and 'Rest' were the same as in Experiment 1, 'RhythmicRest' had five brief pauses during the 30-s time period, and 'DiscreteRest' consisted only of six discrete movements within one 30-s time period. Thus, these two movement conditions balanced the number of start and stops between 'Discrete' and 'Rhythmic' in the two conditions. Six participants contributed to this experiment. Experiment 3, a control experiment, was the same as Experiment 1, except that both rhythmic and discrete movement were triggered and maintained by an auditory metronome signal, denoted as 'RhythmicSound', 'DiscreteSound' and 'RestSound'. Eleven subjects participated in Experiment 3, each performing one session at metronome base frequency of 1.43 Hz and one at 2.14 Hz (see Methods).

In all experiments, we used 4-Tesla fMRI to scan the entire brain in intervals of 5 s, and averaged activities over the normalized brain images of all subjects per experiment. In addition, for six participants, behavioral movement data of all movement conditions was collected outside the scanner. The summary statistics for these data verified that the behavioral data was in accordance with the experimental instructions (**Table 1**). In particular, as it is important for our main results, it should be noted that in Experiment 1 the peak velocity of the discrete movement was not significantly different from that of rhythmic movement, as confirmed with a *t*-test that did not show significance ($P = 0.17$). Thus, the main kinematic parameters of discrete and rhythmic movement in Experiment 1 were comparable.

RESULTS

Experiment 1

As defined according the anatomical notation of Picard and Strick[30], in Experiment 1 (**Fig. 2** and **Table 2**), rhythmic movement activated solely cerebral areas contralateral to the moving wrist (that is, the left hemisphere for the right hand in our experiments), in particular primary sensorimotor and premotor cortices (S1, M1 and PMdc), supplementary motor area (SMA and pre-SMA) and cingulate cortex (RCZp and CCZ). Ipsilateral activation was only found in the cerebellum. The contributions of these brain areas to rhythmic movement are not surprising, as they are all motor areas with direct projections to the spinal cord and/or to M1 and have been found to be involved in simple movements before[30–33]. In contrast, discrete movement showed very different activations in various brain regions, although it was confined to the same joint. Exclusive to discrete movement (**Fig. 2** and **Table 2**), we observed activity in the contralateral hemisphere in the rostral part of the dorsal premotor cortex (PMdr), Broca's area (BA44, the assumed location of mirror neurons in humans[34], a well-studied motor planning area), parietal cortex (BA7, BA40), the anterior part of the rostral cingulate zone (RCZa) and area BA47. Moreover, widespread activation occurred in the ipsilateral cerebral hemisphere and the bilateral cerebellum. These brain regions have

Table 1 Summary statistics of kinematic movement data collected from six subjects outside the scanner

Condition	Amplitude (rad)	Period (s)	Max. velocity (rad/s)	No. movements	No. starts + stops	Inter-movement period (s)	Inter-movement variability (s)	Duration (s)
Rhythmic (Exp. 1)	1.13 (0.27)	0.79 (0.12)	6.20 (1.75)	78.00 (12.75)	2.00 (0.00)			
Discrete (Exp. 1)	1.08 (0.22)		7.18 (2.17)	29.88 (4.80)	59.75 (9.60)	1.00 (0.21)	0.45 (0.36)	0.34 (0.02)
Rhythmic (Exp. 2)	1.20 (0.28)	0.74 (0.13)	6.33 (1.47)	82.62 (15.49)	2.00 (0.00)			
DiscreteRest (Exp. 2)	1.19 (0.27)		7.24 (2.61)	6.14 (1.29)	12.28 (2.58)	4.53 (0.43)	1.10 (1.29)	0.35 (0.03)
RhythmicRest (Exp. 2)	1.19 (0.30)	0.76 (0.12)	6.43 (1.82)	65.50 (8.81)	11.40 (2.30)			
RhythmicSound (Exp. 3–Slow)	1.14 (0.35)	1.38 (0.15)	4.93 (2.22)	44.00 (5.32)	2.00 (0.00)			
DiscreteSound (Exp. 3–Slow)	1.18 (0.34)		6.89 (2.43)	19.00 (1.59)	38.00 (3.18)	1.57 (0.13)	0.67 (0.21)	0.42 (0.04)
RhythmicSound (Exp. 3–Fast)	1.13 (0.33)	0.91 (0.03)	5.35 (2.20)	65.88 (2.25)	2.00 (0.00)			
DiscreteSound (Exp. 3–Fast)	1.17 (0.31)		7.01 (2.28)	27.44 (1.86)	54.88 (3.72)	1.10 (0.07)	0.47 (0.23)	0.38 (0.02)

All data are averages across all subjects; 1 s.d. is indicated in parentheses. Amplitude, period and peak velocity were extracted for every flexion or extension movement individually and then averaged across the trial (see Methods for further details). The number of movements is the sum of the number of flexions plus the number of extensions per trial. Similarly, the number of starts and stops is the sum of the number of movement starts plus the number of movement stops per trial. Inter-movement period is defined as the time between two consecutive discrete movements, and inter-movement variability is the standard deviation of this inter-movement period, which indicates how variably a discrete movement was triggered.

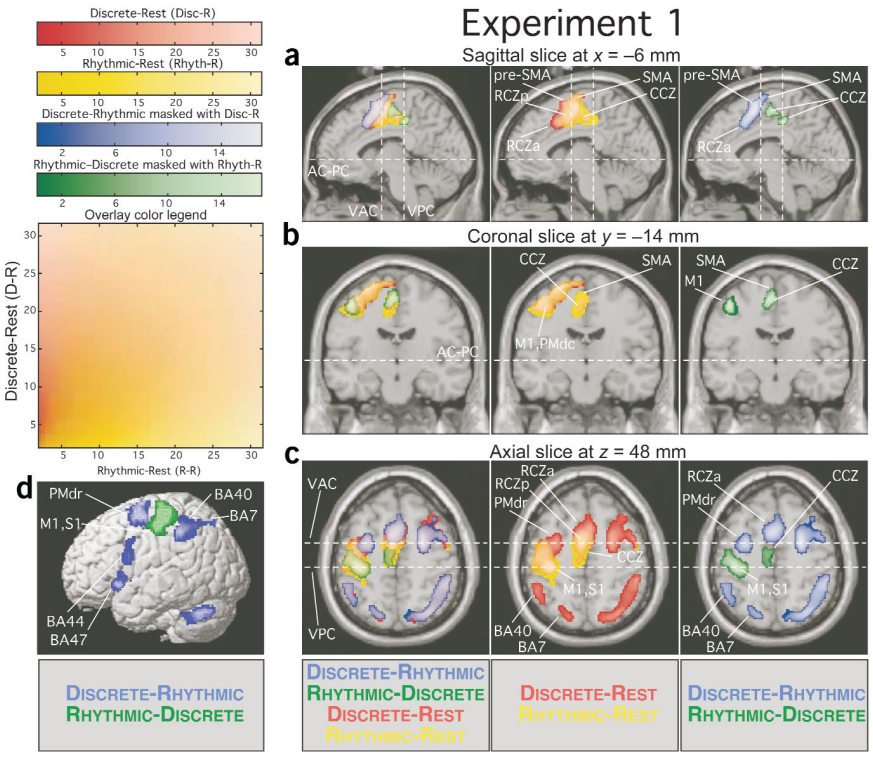

Figure 2 Summary of brain activity in Experiment 1, superimposed on a Montreal Neurological Institute (MNI) coordinates normalized T1 brain template, included in the SPM software distribution. Four different statistical comparisons are displayed in different color codes that denote the *t*-values of the statistical tests (refer to key on the left). 'Rhythmic-Rest' and 'Discrete-Rest' in the middle plots (**a**–**c**) demonstrate the main effects of brain activity during 'Rhythmic' and 'Discrete' movement conditions. When there is overlap between the two contrasts, the Overlay Color Legend on the left of the panels is used to highlight the degree of overlap. 'Rhythmic-Discrete' shows brain areas where rhythmic movement has stronger activity than discrete movement. Only areas that were active in 'Rhythmic-Rest' were permitted to contribute to this contrast by using the active voxels of 'Rhythmic-Rest' as an inclusive mask. Analogously, 'Discrete-Rhythmic' displays areas that showed significantly more activation than rhythmic movement, using 'Discrete-Rest' as an inclusive mask. The right plot of all three panels shows the Rhythmic-Discrete and 'Discrete-Rhythmic' contrasts in isolation for the sake of clarity (no overlap is possible); **Table 2** lists the coordinates of these differential activations. The left plot in all panels superimposes the activities from the other plots in the panel to allow an easy comparison of activation locations. (**d**) The major brain areas of interest are shown on a rendering on the left hemisphere; the areas and color coding correspond to the contrasts in the rightmost images of **a**–**c**. All results shown are statistically significant at a level of $P < 0.05$, corrected for multiple comparisons within the entire brain volume. AC, anterior commissure; PC, posterior commissure; VAC, vertical line perpendicular to the AC-PC, passing through the AC; PAC, vertical line perpendicular to the AC-PC, passing through the PC. All other abbreviations are as in **Table 2**.

been previously observed to participate in point-to-point reaching movements[9,31,35–37] and complex sequential movements[32,38]. All these areas are more associated with planning aspects of movement[30]—that is, they are not primary motor areas. Notably, this difference between rhythmic and discrete movement was insensitive to the threshold of Student's *t*-value used in our SPM analyses: even at the most liberal $P < 0.05$ cutoff (uncorrected for multiple comparisons, not shown in figures or tables), the 'Rhythmic-Rest' contrast did not reveal activity in any of the contralateral motor-related areas specific to discrete movement, that is, PMdr, BA44, BA47, BA7, BA40 and RCZa. Thus, the notable finding was that rhythmic and discrete movement robustly elicited such large differences in activity.

Experiment 2

To test whether the increased and more widespread activity in discrete movement was the result of differences in the functional anatomy of discrete and rhythmic movement and not some other factors, we conducted several control experiments. We proposed that the unequal number of starts and stops in discrete movement could potentially be a source of more brain activation. Moreover, even if peak velocity of rhythmic and discrete movement is roughly the same (**Table 1**), discrete movement usually has stronger acceleration components than rhythmic movement, which could have led to stronger blood oxygen level–dependent (BOLD) signals[39] (although the amount of movement was significantly larger in rhythmic movement, as measured, on average, by the occurrence of 78 flexion and extension movements in one trial compared with about 30 in discrete movement; **Table 1**). To control for such issues, Experiment 2 exactly balanced the number of movement starts and stops, which also entailed significantly less movement in the 'DiscreteRest' condition than in the 'RhythmicRest' condition; the static holding of the wrist between the few discrete movements is unlikely to have influenced our data as it has insignificant effects on BOLD signals[39] (**Tables 1** and **2**; **Fig. 3a**). Note that we focused only on contralateral cerebral and ipsilateral cerebellar activation in Experiment 2 and Experiment 3 (**Table 2**), as these are of prime interest. The findings of Experiment 2 (**Tables 1** and **2**, **Fig. 3a**) demonstrated that although 'DiscreteRest' involved only six movements in 30 s, when contrasted with 'RhythmicRest', it resulted in more activity in almost all brain areas as the 'Discrete–Rhythmic' comparison in Experiment 1 (**Fig. 3a**, right panel, versus **Fig. 2** and **Table 2**)—in particular contralateral BA7, BA40, BA47, PMdr and RCZa. Only for contralateral BA44 and the ipsilateral cerebellum were these differences not statistically significant.

By contrasting the 'RhythmicRest' and 'Rhythmic' conditions (**Fig. 3b**), we also tested which parts of the brain were most likely to be involved in triggering the start and stop of movements. Within the areas of 'Discrete-Rhythmic' from Experiment 1, at the most tolerant statistical threshold ($P < 0.05$, uncorrected, which is the most pessimistic for our results), only contralateral BA40, the ipsilateral cerebellum, a small number of voxels in contralateral pre-SMA and RCZa, and several ipsilateral areas showed activity in this comparison. No activity was observed in contralateral PMdr, BA44, BA47 and BA7.

To summarize Experiment 2, we have strong evidence that at least PMdr, BA7 and BA47 are indeed specific to discrete movement. BA40, BA44, RCZa and the ipsilateral cerebellum seem to be involved to some extent in movement initiation and termination, or perhaps, in

Table 2 Anatomical localization of differential brain activity from all experiments

		Exp. 1: Discrete-Rhythmic					Exp. 2: DiscreteRest–RhythmicRest					Exp. 3: DiscreteSound–RhythmicSound				
Area	Hemisphere	*x*	*y*	*z*	#	*t*	*x*	*y*	*z*	#	*t*	*x*	*y*	*z*	#	*t*
BA 10	Right	28	46	18	239	***8.79										
BA 47	**Left**	**–44**	**17**	**–6**	**189**	***9.64**	**–46**	**14**	**–1**	**##**	***4.66**	**–44**	**17**	**–6**	**153**	**6.52**
BA 47	Right	40	17	–3	406	***8.75**										
BA 40	**Left**	**–45**	**–44**	**47**	**514**	***8.22**	**–50**	**–46**	**48**	**64**	**3.94**	**–44**	**–46**	**52**	**145**	**3.19**
BA 40	Right	48	–36	47	489	***11.59**										
		61	–33	31	513	***11.10**										
BA 9 & BA 44	**Left**	**–59**	**9**	**20**	**152**	***9.03**				**0**		**–53**	**6**	**37**	**12**	**4.18**
BA 9 & BA 44	Right	50	15	25	187	***7.17**										
BA 7	**Left**	**–14**	**–67**	**51**	**92**	***7.43**	**–12**	**–69**	**50**	**24**	**3.54**	**–14**	**–66**	**49**	**10**	**2.95**
BA 7	Right	32	–63	51	493	***10.9**										
BA 8	Right	53	14	40	248	***8.64**										
Cereb. uvula	Left	–24	–69	–25	63	***6.74**										
Cereb. culmen/tuber	Left	–40	–52	–29	463	***11.33**										
Cereb. culmen/tuber	**Right**	**40**	**–54**	**–29**	**150**	***8.31**				**0**		**50**	**–54**	**–29**	**131**	***5.99**
PMdr	**Left**	**–26**	**0**	**48**	**365**	***11.35**	**–32**	**8**	**51**	**54**	**2.99**	**–36**	**1**	**55**	**414**	***7.36**
PMdr	Right	26	3	51	743	***14.45**										
Pre-SMA	**Left**	**–2**	**5**	**55**	**429**	***11.88**	**–2**	**11**	**55**	**##**	***4.62**	**–2**	**8**	**51**	**339**	***13.63**
Pre-SMA	Right	2	9	55	682	***11.95**										
RCZp	**Left**	**–2**	**12**	**43**	**223**	***11.54**	**–2**	**25**	**34**	**##**	***4.49**	**–4**	**14**	**45**	**369**	***15.56**
RCZa	Right	4	23	32	187	***9.43**										
RCZp	Right	2	12	45	265	***12.09**										

		Exp. 1: Rhythmic-Discrete					Exp. 2: RhythmicRest–DiscreteRest					Exp. 3: RhythmicSound–DiscreteSound				
Area	Hemisphere	*x*	*y*	*z*	#	*t*	*x*	*y*	*z*	#	*t*	*x*	*y*	*z*	#	*t*
CCZ/SMA	**Left**	**–4**	**–11**	**54**	**134**	***7.32**	**–2**	**–7**	**50**	**17**	**2.84**	**–2**	**–19**	**45**	**64**	**3.35**
		–2	**–21**	**42**	**99**	***6.39**						**–10**	**–25**	**40**	**134**	***5.10**
Cereb. culmen	**Right**	**22**	**–49**	**–16**	**633**	***9.73**	**26**	**–51**	**–16**	**##**	**3.29**	**26**	**–47**	**–16**	**633**	***9.39**
M1/S1	**Left**	**–38**	**–22**	**56**	**###**	***15.00**	**–34**	**–16**	**62**	**##**	**3.61**	**–38**	**–21**	**54**	**###**	***15.52**

Localization was done using Cartesian *x,y,z* coordinates of the atlas of Talairach and Tournoux[43]. #, number of 2 × 2 × 2 mm voxels in a cluster as determined by SPM at $P < 0.05$ (corrected for multiple comparisons for the volume of interest; see Methods). *t*, *t*-value (Student *t*-test) for the most activated voxel in a cluster. ***$P < 0.0001$, **$P < 0.005$, *$P < 0.05$. Owing partially to large cluster sizes (**Figs. 2** and **3**), brain coordinates between experiments seem to have more variance than was actually present, as it is highly random which voxel in such large clusters happens to be the most activated one. Rows in boldface type denote areas that are directly involved in the control of the right wrist: that is, the left cerebral and the right cerebellar hemisphere. In Experiments 2 and 3, we focused our analyses only on these regions. Abbreviations[30]: CCZ, caudal cingulate zone; RCZ, rostral cingulate zone, consisting of anterior (RCZa) and posterior (RCZp) portions; SMA, caudal portion of the supplementary motor area, corresponding to SMA proper; pre-SMA, rostral portion of the supplementary motor area; M1, primary motor cortex; S1, primary sensory cortex; PMdr, rostral part of the dorsal premotor cortex; PMdc, caudal part of the dorsal premotor cortex; cereb., cerebellum; BA, Brodman area; BA 7, precuneus in parietal cortex; BA 8, middle frontal gyrus; BA 9, middle frontal gyrus; BA 10, anterior frontal lobe; BA 47, inferior frontal gyrus; BA 40, inferior parietal cortex; BA 44, Broca's area.

the case of BA44 and the ipsilateral cerebellum, were affected by a potentially larger effort involved in the discrete movement condition in Experiment 1.

Given the distinct activity of PMdr, BA7 and BA47 in discrete movement even in the stringent control Experiment 2, we believe that these results provide strong evidence to refute the hypothesis that rhythmic movement is generated with the help of the discrete movement system: in other words, RA ⊇ DA is not supported.

Experiment 3

Experiment 3 examined whether the cognitive effort of self-pacing of randomized discrete movements could have contributed to the difference of brain activation between discrete and rhythmic movement. Essentially, we repeated Experiment 1 with auditory pacing from a metronome that provided the movement frequency in rhythmic movement, and the randomized movement onsets in discrete movement, by means of a change in pitch frequency (see Methods section). We also examined two different pacing frequencies, 1.43 Hz and 2.14 Hz. This experiment obtained qualitatively the same results as Experiment 1 (**Tables 1** and **2**). Because the difference in movement frequencies in the two sound conditions only affected the intensity of activation in some areas, anatomical locations averaged over all sound sessions and subjects are shown (**Table 2**). As can be recognized from the *t*-values, except for pre-SMA and RCZp, contralateral cerebral brain activations in metronome-paced movement were, in general, significantly lower than in self-paced movement, a difference that seems to be common when comparing self-pacing and external pacing[38].

DISCUSSION

Approaches to understanding the neural and behavioral basis of arm movements have been traditionally divided into two separate fields: one focusing on rhythmic pattern generators[1] and the other on visually guided trajectory formation of reach and grasp movements[10,11,16]. Consequently, both fields have developed computational models of

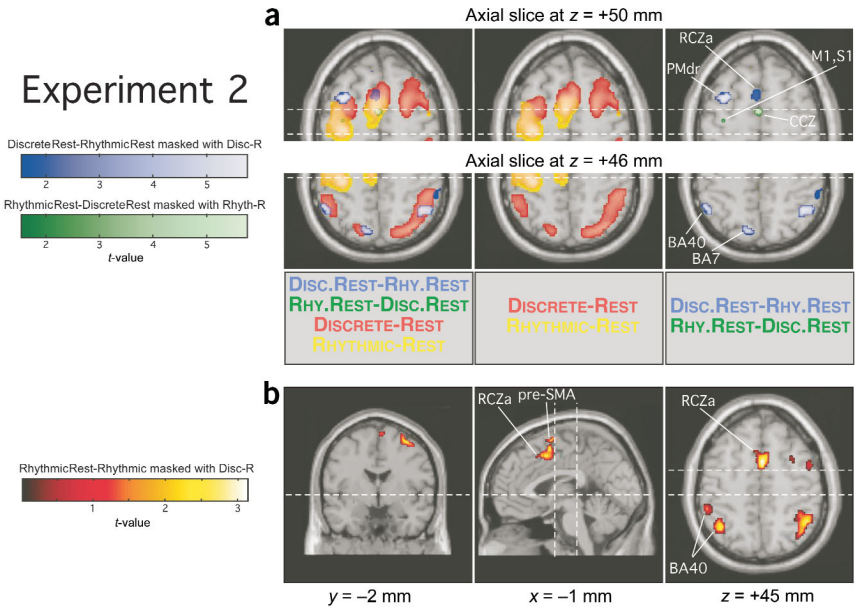

Figure 3 Summary of brain activations of Experiment 2. (**a**) The middle plot in both rows shows the main effects of 'RhythmicRest' and 'DiscreteRest' from Experiment 1 as a comparison, that is, the red, yellow and orange activations are the same as in **Figure 2**. 'DiscreteRest–RhythmicRest' (blue) shows brain areas where the 'DiscreteRest' condition has stronger activity than the 'RhythmicRest' condition. Similarly, 'RhythmicRest–DiscreteRest' (green) denotes brain activity where 'RhythmicRest' had more activity than 'DiscreteRest'. Activations are statistically significant at $P < 0.05$ corrected for multiple comparisons for the spatial hypotheses created from Experiment 1 (see Methods). Color bars on the left of the figure indicate the magnitude of *t*-values. The left plot superimposes the middle and right plot. The figure should be compared to brain areas in **Figure 2.** (**b**) Brain areas where the 'RhythmicRest' condition has stronger activation than the 'Rhythmic' condition. Only areas that were active in 'Discrete-Rest' from Experiment 1 were permitted to contribute to this contrast by using the active voxels of 'Discrete-Rest' as an inclusive mask. Activations are statistically significant at $P < 0.05$ (uncorrected for multiple comparisons; see color bars on the left of figure for *t*-values).

arm movement generation that differ in philosophy: pattern generator theories seek an explanation for behavioral phenomena more in the self-organization of coupled nonlinear dynamic systems, whereas discrete reaching and grasping movements were explained more in the formal framework of optimal control. For the sake of a coherent theory, models of pattern generators were extended to account for discrete movement as a special case, and models of discrete trajectory formation incorporated rhythmic movement as a particular implementation. Because of these different philosophies, there is rather little interaction between researchers from these competing fields.

To determine whether discrete and rhythmic arm movements have a common neural basis, in the experiments reported here we investigated the difference in brain activation between rhythmic and discrete single-joint wrist movement in a functional neuroimaging experiment. Our principal finding is that whereas rhythmic movement activated only a small number of unilateral primary motor areas (M1, S1, PMdc, SMA, pre-SMA, CCZ, RCZp and cerebellum), discrete movement activated a variety of additional contralateral nonprimary motor areas (BA7, BA40, BA44, BA47, PMdr and RCZa) and, moreover, showed very strong bilateral activity in both the cerebrum and cerebellum. Control experiments examined whether in discrete movement the much more frequent movement initiation and termination and the associated cognitive effort could account for the observed differences. Only BA40, BA44, RCZa and the cerebellum were potentially involved in such issues, which left BA7, BA47 and PMdr, as well as a large amount of bilateral activation, as unique features in discrete movement. Because rhythmic movement activates significantly fewer brain areas than discrete movement, there does not seem to be support for the concept that rhythmic movement is generated on top of a discrete movement system: that is, rhythmic arm movement is not composed of discrete strokes.

Given that rhythmic movement is not a special case of discrete movement, it might be that discrete movement is a special case of rhythmic movement, indicated by RA $\subseteq$ DA, as detailed earlier. Rhythmic movement is accompanied by stronger activity in M1/S1, SMA, CCZ and the ipsilateral cerebellum (**Fig. 2** and **Table 2**). However, all these activations can also be found in discrete movement, just to a lesser degree (**Fig. 2**), and BOLD activity in these areas is affected by the amount of movement in an experimental condition[32,38]; our own data, by comparing the fast with the slow sound sessions in Experiment 3, showed similar movement rate dependencies. Thus, within the range of our current fMRI recordings, RA $\subseteq$ DA is supported, and discrete movement could indeed be generated with the help of the rhythmic movement system.

Our results have an interesting parallel to a recent review on brain activity seen in association with timing[40]. Here, the authors argue that there are distinct brain structures involved in tasks depending on whether these are characterized more by automatic or more by cognitive control. Automatic control primarily draws on primary motor circuits, whereas cognitive control requires additional prefrontal and parietal areas. For example, central pattern generators would be a suitable candidate for the generation of timing in automatic tasks, whereas memory and attention systems are also involved in cognitively controlled tasks, which require more elaborate timing, such as is necessary in complex movement planning. From this view, one would intuitively classify rhythmic movement as automatic control and discrete movement as cognitive control, and our data provides perfectly matching empirical evidence to support this view even in as simple a movement as wrist flexion-extension.

In summary, our data provides the first empirical evidence that discrete and rhythmic movements, even when performed with the same single joint, use very different brain circuitries. Single-joint discrete movement activates the same brain areas as have been found to be activated in complex reaching and pointing experiments, indicating that, even in such a simple discrete movement, higher-level planning areas are recruited. In contrast, rhythmic movement shows much less cerebral brain activity: that is, only contralateral areas that are known to be major motor areas are activated, but no known higher planning areas. From a theoretical point of view, this reduced activity in rhythmic movement is not surprising, as rhythmic pattern generation is computationally much easier to realize (a pair of mutually inhibitory leaky-integrator neurons suffices[41]) than the more complex acceleration and deceleration profiles of discrete movement. The brain activa-

tion in rhythmic movement may thus indicate areas that could be involved in a cortical pattern generator, and SMA, pre-SMA, RCZp, CCZ and the cerebellum might be of particular interest in this respect. Further neuroimaging and electrophysiological studies are needed to elucidate the details of these circuits. Notably, the entire functional rhythmic movement circuit is included in the discrete circuit, leaving open the possibility that discrete movement is indeed based on modulating the original pattern generator loop, for example, by smoothly aborting the rhythmic movement after half a period. The areas that are specific to discrete movement only, that is, PMdr, BA7 and BA47, could contribute to the timing and required memory of such operations[40]. However, our current data do not provide further details on this issue. As an alternative to assuming that the rhythmic movement circuit is part of the discrete circuit, some recent data provide evidence of the coexistence of rhythmic and discrete movement in single-joint elbow flexion-extension[23,24] tasks, thus supporting the hypothesis that rhythmic and discrete movement might be separate circuits. What our data strongly support, however, is that rhythmic movement is not based on the use of the discrete movement systems. Thus, in order to fully understand the neurobiological mechanisms of discrete movement, it may first be necessary to better understand those of rhythmic movement, or to consider rhythmic movement as a separate fundamental movement primitive that requires distinct neurophysiological realizations and theoretical modeling.

METHODS

Task. Participants performed flexion-extension wrist movements with their right hand while lying supine in an MRI scanner. Head movements were restrained by vacuum beanbag pillows (Olympic Medical) surrounding the head, neck and shoulders. The right arm was strapped in a pronated orientation into a horizontal cast so that only the wrist could be moved freely. Flexions and extensions were performed in a vertical up-and-down movement that avoided any impact with the scanner bore. Visual feedback from the wrist movement was blocked by a paper screen. Participants were given a roughly table tennis ball–sized paper ball to hold such that the fingers of the hand were constrained in a well-defined posture. Through a tilted mirror, a rear-projection screen outside of the scanner was visible to the participants. During each movement condition, the name of the condition was displayed on the screen; no other cues were given during the experiment. The experimenter continuously monitored the correctness of participants' movements through a video camera outside of the scanner. The experimental procedure was approved by the local institutional review board.

Experiment 1. Eleven participants performed in Experiment 1, which followed an epoch-based design with three movement conditions. Each condition was performed for 30 s and pseudo-randomly repeated four times in one session. Two sessions were collected for each participant. The movement condition 'Rhythmic' involved a continuous, smooth alternation between flexion and extension of the wrist at the participant's individual comfort frequency, usually chosen in the order of 1.5 Hz within a 60–80° angular amplitude. The movement condition 'Discrete' required moderately fast and discrete point-to-point movements, either from flexion to extension if the wrist was previously flexed, or from extension to flexion if the wrist was previously extended. The participants were instructed to perform a movement amplitude of about 80% of the possible movement range, and the movement speed was kept about the same as during one half-cycle of the oscillatory movement. Participants were trained to randomly insert a pause between individual discrete movements (on the order of up to 1 s long) and to avoid a periodic triggering of discrete movements. Thus, about 30–40 discrete movements were performed in a 30-s block. The third movement condition was 'Rest', that is, no movement at all. **Figure 1** illustrates a typical realization of the movement conditions.

Experiment 2. This experiment similarly used an epoch-based design with four movement conditions and had six participants. Each condition was performed for 30 s and was pseudo-randomly repeated four times in one session. Two sessions were collected for each participant. The movement conditions 'Rhythmic' and 'Rest' were the same as in Experiment 1, whereas the movement condition 'RhythmicRest' was the same as 'Rhythmic', except that participants paused the rhythmic movement five times at random, but with sufficiently long intervals (on the order of approximately 4–6 s) such that a 30-s trial included six start and stops of the rhythmic movement. Movement condition 'DiscreteRest' consisted of only six discrete movements, using random but sufficiently long (about 4–6 s) pauses between the individual discrete movements. Thus, the number of start-and-stops was balanced between the 'RhythmicRest' and 'DiscreteRest' conditions, and the actual amount of movement time in 'DiscreteRest' was very short compared to 'RhythmicRest'.

Experiment 3. This experiment was identical to Experiment 1, except that sound-pacing was used instead of self-initiated movement. Through their headsets, subjects could hear a metronome beep at a certain frequency. The beep was presented with the same frequency in all conditions of a session, that is, 'RhythmicSound', 'DiscreteSound' and 'RestSound'. In 'RhythmicSound', the pitch of the beep of the metronome alternated between a high and a low value, such that one period of rhythmic movement corresponded to two beeps, that is, one high- and one low-pitch beep. In 'DiscreteSound', a high-pitch beep signaled participants to initiate a new flexion or extension movement, whereas a low-pitch beep signaled them to finish this flexion or extension movement and/or not to move. During the interval between two discrete movements, the low-pitch beep continued to be presented in a rhythmic fashion. Thus, discrete movement could be triggered in a randomized fashion by inserting high-pitch beeps at random times in the metronome beep sequence. In 'RestSound', only low-pitch beeps were presented rhythmically. Eleven subjects performed two sessions each, one using a 1.43-Hz metronome frequency and one using 2.14 Hz. These frequencies corresponded to either 0.71 Hz or 1.07 Hz of rhythmic movement and were determined in pilot experiments outside of the scanner, such that movement was not perceived to be too slow or too fast by the subjects. These frequencies also allowed a reasonably high time resolution to trigger discrete movements.

Participants. Seventeen neurologically normal, fMRI-experienced subjects (25–43 years of age; seven females and ten males) participated in the two experiments. Each participant gave informed written consent before the experiment. Participants were trained outside of the scanner until they could perform the experimental conditions properly. Pseudo-random pauses between discrete movements were initially trained with the sound cue used in Experiment 3. On average, 10 min of training sufficed for participants to become comfortable with the tasks.

Behavioral data acquisition. For six subjects, we recorded wrist movement kinematics outside of the scanner for all experimental conditions using a Sarcos Sensuit (Sarcos Inc.), an exoskeleton that directly measures joint angular data with Hall effect sensors. Position data was sampled at 100 Hz.

Behavioral data analysis. Position data was first centered by subtracting the mean of each trajectory, then numerically differentiated to obtain movement velocities, and digitally low-pass filtered with a second-order Butterworth filter using a 5-Hz cutoff frequency. By analyzing amplitude and zero crossing information of both position and velocity data, we extracted descriptive statistics of the movement, such as amplitude, period, peak velocity, the number of movements and the number of start and stops in rhythmic movement, as well as amplitude, peak velocity, movement duration, number of movements, number of start and stops, inter-movement period and inter-movement variability of discrete movement.

Amplitude, period and peak velocity were extracted for every flexion or extension movement individually and then averaged across the trial. The number of movements was the sum of the number of flexions plus the number of extensions per trial. Similarly, the number of starts and stops was the sum of the number of movement starts plus the number of movement stops per trial. Inter-movement period was defined as the time between two consecutive discrete movements, and inter-movement variability was the standard deviation of the inter-movement period, which indicates how randomly a discrete movement was triggered.

Each statistic was first extracted in a trial-specific manner, and then averaged across all subjects.

Acquisition. Experiments were performed on a 4.0-Tesla Varian Siemens UNITY INOVA whole-body imaging system equipped with whole-body shielded gradients to obtain BOLD contrast functional images. Twenty-four contiguous axial slices were used to image the entire brain. Functional data were collected using navigator echo-corrected T2*-weighted segmented gradient echoplanar imaging (24 slices; 64 × 64 resolution; 20 cm in plane field of view (FOV); time to echo (TE) of 15 ms; volume acquisition time of 5 s; and a voxel size of 3.1 × 3.1 × 6 mm). Functional data were superimposed on prepared high-resolution three-dimensional inversion T1-weighted anatomical images of the brain (64 slices; 256 × 256; TE of 6.2 ms; time to relaxation of 11.4 ms) using a phase reference image that corrected for high-field geometric distortions.

MRI analysis. Data analysis was performed with SPM2 (Wellcome Department of Cognitive Neurology). First, motion artifacts in all functional images were removed by realigning images to the first functional image of each session. Second, anatomical images were co-registered with functional images. Third, anatomical images were stereotactically transformed to a standard template in SPM, and this normalization was applied to all co-registered functional images. As we noted that SPM did not achieve very accurate normalization in some subjects, we manually corrected the normalization parameters when needed with an additional affine transformation that used major brain landmarks (commissures, overall brain dimensions and sulci) as normalization criteria. To enable cross-subject analyses, standardized images were spatially smoothed with a 6-mm (full width at half maximum) Gaussian filter (other filter sizes were explored without an effect on the results of our experiments being observed). Before statistical data analysis, voxel time series were temporally high-pass filtered (120 s cutoff period) to remove slow trends in the data, and temporally low-pass filtered with a hemodynamic response filter[42]. Global scaling of the functional data was applied to normalize activity across subjects and different scanning days. Areas of significant change in the brain were determined using *t*-statistics (SPM{*t*}) in a fixed-effects analysis and a box-car design of the conditions, convolved with the hemodynamic response function. We used the effective degree of freedom adjusted for analysis of fMRI data[42]. In assessing the statistical significance of activations, we corrected for multiple comparisons based on Gaussian random field theory in terms of spatial extent at a threshold of $P < 0.05$ for all experiments. Either the entire brain (Experiment 1) or more focused spatial hypotheses (Experiments 2 and 3) were used (see below). For reporting spatial locations of activation, we used the atlas of Talairach and Tournoux[43], derived from the Montreal Neurology Institute (MNI) coordinates in SPM by a coordinate transformation[44].

For the analysis of Experiment 1, when determining differences between discrete and rhythmic activity, we always applied an additional mask according to the main effects of the movement condition of interest. For the contrast 'Discrete-Rhythmic', we applied the mask 'Discrete-Rest' as an inclusive mask to ensure that only voxels that were truly active in discrete movement would be eligible for contributing to findings in 'Discrete-Rhythmic'; analogously, for 'Rhythmic-Discrete', we used the mask 'Rhythmic-Rest'. Masks were determined as the areas of activation at a threshold of $P < 0.05$ corrected for multiple comparisons in the entire brain volume; no spatial extent threshold was applied to eliminate very small activation clusters, as all activations were of significant cluster size (**Table 2**).

For the analyses of Experiment 2 and Experiment 3, we used SPM's small volume correction feature to determine statistical significance[45]. For this purpose, activated brain areas from Experiment 1 (obtained at $P < 0.05$ corrected for multiple comparisons in the entire brain volume and masked as described above) were extracted with the MarsBaR toolbox of SPM[46]. The individual regions were converted into spatial hypothesis masks. Contrasts for Experiment 2 and 3 were first determined at $P < 0.05$ uncorrected, and subsequently we applied small volume correction with the help of the MarsBaR masks for every area that was active in Experiment 1. Thus, we determined which of the areas of Experiment 1 were active/inactive in Experiments 2 and 3. Significance was determined at $P < 0.05$ corrected for multiple comparisons within the spatial hypothesis mask; no spatial extent threshold was applied.

ACKNOWLEDGMENTS

This research was supported in part by US National Science Foundation grants ECS-0325383, IIS-0312802, IIS-0082995, ECS-0326095 and ANI-0224419, the ERATO Kawato Dynamic Brain Project funded by the Japanese Science and Technology Agency, and the National Institute of Information and Communications Technology (NICT).

COMPETING INTERESTS STATEMENT

The authors declare that they have no competing financial interests.

Received 20 July 2004; accepted 13 September 2004
Published online at http://www.nature.com/natureneuroscience/

1. Marder, E. Motor pattern generation. *Curr. Opin. Neurobiol.* **10**, 691–698. (2000).
2. Lamb, T. & Yang, J.F. Could different directions of infant stepping be controlled by the same locomotor central pattern generator? *J. Neurophysiol.* **83**, 2814–2824. (2000).
3. Pinter, M.M. & Dimitrijevic, M.R. Gait after spinal cord injury and the central pattern generator for locomotion. *Spinal Cord* **37**, 531–537 (1999).
4. Dimitrijevic, M.R., Gerasimenko, Y. & Pinter, M.M. Evidence for a spinal central pattern generator in humans. *Ann. N. Y. Acad. Sci.* **860**, 360–376 (1998).
5. Kelso, J.A.S. *Dynamic Patterns: The Self-Organization of Brain and Behavior* (MIT Press, Cambridge, Massachusetts, USA, 1995).
6. Turvey, M.T. Coordination. *Am. Psychol.* **45**, 938–953 (1990).
7. Kugler, P.N. & Turvey, M.T. *Information, Natural Law, and the Self-Assembly of Rhythmic Movement* (Erlbaum, Hillsdale, New Jersey, USA, 1987).
8. Andersen, R.A., Snyder, L.H., Bradley, D.C. & Xing, J. Multimodal representation of space in the posterior parietal cortex and its use in planning movements. *Annu. Rev. Neurosci.* **20**, 303–330 (1997).
9. Kalaska, J.F., Scott, S.H., Cisek, P. & Sergio, L.E. Cortical control of reaching movements. *Curr. Opin. Neurobiol.* **7**, 849–859 (1997).
10. Sabes, P.N. The planning and control of reaching movements. *Curr. Opin. Neurobiol.* **10**, 740–746 (2000).
11. Flash, T. & Sejnowski, T. Computational approaches to motor control. *Curr. Opin. Neurobiol.* **11**, 655–662 (2001).
12. Morasso, P. Spatial control of arm movements. *Exp. Brain Res.* **42**, 223–227 (1981).
13. Abend, W., Bizzi, E. & Morasso, P. Human arm trajectory formation. *Brain* **105**, 331–348 (1982).
14. Flash, T. & Hogan, N. The coordination of arm movements: An experimentally confirmed mathematical model. *J. Neurosci.* **5**, 1688–1703 (1985).
15. Uno, Y., Kawato, M. & Suzuki, R. Formation and control of optimal trajectory in human multijoint arm movement — Minimum torque-change model. *Biol. Cybern.* **61**, 89–101 (1989).
16. Kawato, M. Internal models for motor control and trajectory planning. *Curr. Opin. Neurobiol.* **9**, 718–727 (1999).
17. Feldman, A.G. Superposition of motor programs. I. Rhythmic forearm movements in man. *Neuroscience* **5**, 81–90 (1980).
18. Latash, M.L. *Control of Human Movement* (Human Kinetics, Champaign, Illinois, USA, 1993).
19. Soechting, J.F. & Terzuolo, C.A. Organization of arm movements in three dimensional space. Wrist motion is piecewise planar. *Neuroscience* **23**, 53–61 (1987).
20. Sternad, D. & Schaal, D. Segmentation of endpoint trajectories does not imply segmented control. *Exp. Brain Res.* **124**, 118–136 (1999).
21. Schaal, S. & Sternad, D. Origins and violations of the 2/3 power law in rhythmic 3D movements. *Exp. Brain Res.* **136**, 60–72 (2001).
22. Richardson, M.J. & Flash, T. Comparing smooth arm movements with the two-thirds power law and the related segmented-control hypothesis. *J. Neurosci.* **22**, 8201–8211 (2002).
23. Sternad, D., Dean, W.J. & Schaal, S. Interaction of rhythmic and discrete pattern generators in single joint movements. *Hum. Mov. Sci.* **19**, 627–665 (2000).
24. Sternad, D., De Rugy, A., Pataky, T. & Dean, W.J. Interaction of discrete and rhythmic movements over a wide range of periods. *Exp. Brain Res.* **147**, 162–174 (2002).
25. Wei, K., Wertman, G. & Sternad, D. Interactions between rhythmic and discrete components in a bimanual task. *Motor Control* **7**, 134–155 (2003).
26. Smits-Engelsman, B.C., Van Galen, G. P. & Duysens, J. The breakdown of Fitts' law in rapid, reciprocal aiming movements. *Exp. Brain Res.* **145**, 222–230 (2002).
27. Ijspeert, A., Nakanishi, J. & Schaal, S. in *Advances in Neural Information Processing Systems 15* (eds. Becker, S., Thrun, S. & Obermayer, K.) 1547–1554 (MIT Press, Cambridge, Massachusetts, USA, 2003).
28. de Rugy, A. & Sternad, D. Interaction between discrete and rhythmic movements: reaction time and phase of discrete movement initiation during oscillatory movements. *Brain Res.* **994**, 160–174 (2003).
29. Sternad, D. & Dean, W.J. Rhythmic and discrete elements in multi-joint coordination. *Brain Res.* **989**, 152–171 (2003).
30. Picard, N. & Strick, P.L. Imaging the premotor areas. *Curr. Opin. Neurobiol.* **11**, 663–672 (2001).
31. Seitz, R.J., Stephan, K.M. & Binkofski, F. Control of action as mediated by the human frontal lobe. *Exp. Brain Res.* **133**, 71–80 (2000).
32. Gordon, A.M., Lee, J.H., Flament, D., Ugurbil, K. & Ebner, T.J. Functional magnetic resonance imaging of motor, sensory, and posterior parietal cortical areas during performance of sequential typing movements. *Exp. Brain Res.* **121**, 153–166 (1998).
33. Debaere, F. *et al.* Brain areas involved in interlimb coordination: a distributed network. *Neuroimage* **14**, 947–958 (2001).
34. Rizzolatti, G. & Arbib, M.A. Language within our grasp. *Trends Neurosci.* **21**, 188–194 (1998).
35. Kertzman, C., Schwarz, U., Zeffiro, T.A. & Hallett, M. The role of posterior parietal

cortex in visually guided reaching movements in humans. *Exp. Brain Res.* **114**, 170–183 (1997).
36. Grafton, S.T., Fagg, A.H., Woods, R.P. & Arbib, M.A. Functional anatomy of pointing and grasping in humans. *Cereb. Cortex* **6**, 226–237 (1996).
37. Fink, G.R., Frackowiak, R.S., Pietrzyk, U. & Passingham, R. E. Multiple nonprimary motor areas in the human cortex. *J. Neurophysiol.* **77**, 2164–2174 (1997).
38. Deiber, M.P., Honda, M., Ibanez, V., Sadato, N. & Hallett, M. Mesial motor areas in self-initiated versus externally triggered movements examined with fMRI: effect of movement type and rate. *J. Neurophysiol.* **81**, 3065–3077 (1999).
39. Thickbroom, G. W. *et al.* Differences in functional magnetic resonance imaging of sensorimotor cortex during static and dynamic finger flexion. *Exp. Brain Res.* **126**, 431–438 (1999).
40. Lewis, P.A. & Miall, R.C. Distinct systems for automatic and cognitively controlled time measurement: evidence from neuroimaging. *Curr. Opin. Neurobiol.* **13**, 250–255 (2003).
41. Brown, T.G. On the nature of the fundamental activity of the nervous centres; together with an analysis of rhythmic activity in progression, and a theory of the evolution of function in the nervous system. *J. Physiol. (Lond.)* **48**, 18–46 (1914).
42. Turner, R., Howseman, A., Rees, G.E., Josephs, O. & Friston, K. Functional magnetic resonance imaging of the human brain: data acquisition and analysis. *Exp. Brain Res.* **123**, 5–12 (1998).
43. Talairach, J. & Tournoux, P. Co-Planar Stereotaxic Atlas of the Human Brain: 3-Dimensional Proportional System: An Approach to Cerebral Imaging (Thieme, Stuttgard, Germany, 1988).
44. Brett, M., Christiff, K., Cusack, R. & Lancaster, J. Using the Talairach atlas with the MNI template. *Neuroimage* **13**, S85 (2001).
45. Friston, K.J., Frith, C.D., Liddle, P.F. & Frackowiak, R.S.J. Comparing functional (PET) images: the assessment of significant change. *J. Cereb. Blood Flow Metab.* **11**, 690–699 (1991).
46. Brett, M., Anton, J.-L., Valabregue, R. & Poline, J.-B. in *8th International Conference on Funcational Mapping of the Human Brain* (Sendai, Japan, 2002).