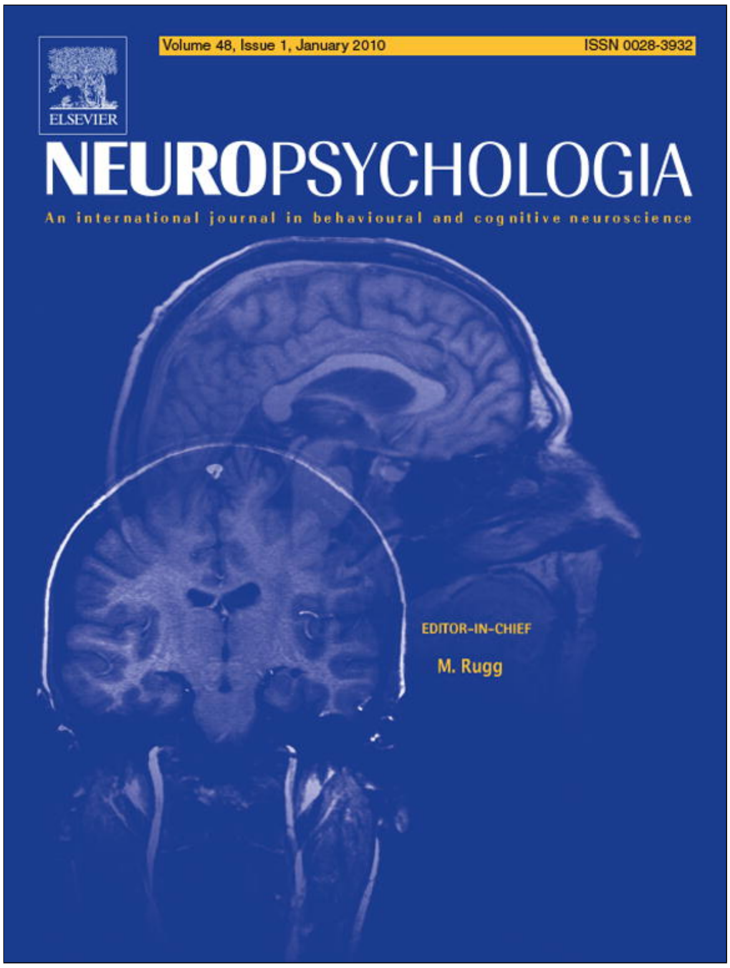
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Automaticity and attention in Huntington's disease: When two hands are not better than one

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A B S T R A C T

People with Huntington's disease (HD) commonly report difficulty carrying out two everyday tasks simultaneously. This difficulty, confirmed by experimental studies, is typically ascribed to impaired attention. Yet, dual-task problems extend to relatively simple tasks, such as walking and talking, which would ordinarily be considered relatively undemanding of attention. The study tests the hypothesis that in HD there is a deficit in the ability to automatise task performance. Thus, simple tasks, which place minimal demands on conscious attention in healthy controls, make disproportionately high demands on attentional resources in HD. We examined the performance of HD patients and healthy controls on a simple, paced finger-tapping task, comparing single-task (tapping with one hand) and dual-task (tapping with both hands simultaneously) performance. For HD patients, bimanual tapping increased the task demands: there was greater variability in tapping rate and patients reported that the 'dual-task' condition was more difficult. The opposite pattern was observed for controls. Variability in tapping performance in HD was highly correlated with performance on cognitive tasks that have the potential to be automatised but not with performance on tasks that are more demanding of executive control, suggesting a common substrate for cognitive and motor automaticity. The data support the hypothesis that HD patients are impaired in their capacity for automisation, and suggest that impaired automaticity may be one source of attentional deficits in HD. The findings have implications for the interpretation of 'high level' deficits in attention and executive function previously reported in HD.

1. Introduction

Huntington's disease (HD) is an inherited autosomal dominant neurodegenerative disorder characterised by motor abnormalities, psychiatric symptoms and cognitive impairment (Harper, 2002). The caudate nucleus and putamen are the earliest site of pathology (Aylward et al., 2004; Vonsattel et al., 1985). Executive impairments represent the prevailing domain of cognitive change (Brandt & Butters, 1996; Craufurd & Snowden, 2002), in keeping with disruption to striatofrontal pathways.

Attention is widely reported to be impaired in HD. Deficits have been demonstrated on tests of vigilance and divided attention (Sprengelmeyer, Lange, & Homberg, 1995), selective attention (Roman et al., 1998) and attentional set-switching (e.g. Aron et al., 2003; Josiassen, Curry, & Mancall, 1983; Lawrence et al., 1996). Problems in attentional set-shifting include difficulties in *conceptual* shifting of mental set, as demonstrated by traditional 'frontal lobe' tests such as the Wisconsin card sorting test (e.g. Josiassen et al., 1983) and its computer analogue, the CANTAB visual discrimination learning test (Lange, Sahakian, Quinn, Marsden, & Robbins, 1995; Lawrence et al., 1998, 1996). However, problems extend also to more basic attentional processes, such as in shifting *visual* or *tactile* spatial attention. A difficulty in disengaging visual attention from cued locations has been reported by some authors (Couette, Bachoud-Lévi, Brugieres, Sieroff, & Bartolomeo, 2008) and a difficulty in shifting tactile attention to unexpected locations by others (Georgiou, Bradshaw, Phillips, & Chiu, 1996). Subtle set-shifting abnormalities can be observed even in premanifest HD, before the onset of physical symptoms and signs (Lawrence et al., 1998), which suggests

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that attentional problems are a fundamental feature of the condition.

The precise basis of patients' attentional difficulties remains a subject of debate. It has been argued that there is a primary impairment in shifting cognitive set in HD (Lawrence et al., 1998). Another interpretation is that patients have a deficit in attentional resource allocation (Georgiou et al., 1996). Both explanations are plausible, and would be consistent with the reports of patients themselves, and of their families, of a difficulty in 'multi-tasking', that is, in carrying out more than one task simultaneously.

To date, relatively few studies have explicitly investigated dual-task performance in HD. The available evidence suggests that deficits may be present across a range of tasks, involving both cognitive and motor demands. Sprengelmeyer et al. (1995) found that HD patients were slower to respond and detected fewer targets on a divided attention task requiring simultaneous monitoring of auditory and visual modalities. Brown, Jahanshahi, and Marsden (1993) reported impaired performance on concurrent peg placement and finger-tapping tasks. More recently, Delval et al. (2008) demonstrated that HD patients' gait was adversely affected by the presence of a secondary task. Interestingly, it was affected more when the secondary task was cognitive (counting backwards) than when it was motor (carrying a tray with four glasses). This latter finding is of particular interest because it mirrors a commonly witnessed clinical phenomenon of HD. If asked a question while walking, HD patients may stop walking before answering the question. That is, they appear to have difficulty walking and talking simultaneously.

An interpretation of dual-task deficits in terms of impaired attentional set shifting or resource allocation would have difficulty accounting for the fact that patients' difficulties in carrying out two tasks extends to tasks, such as walking and talking, which under normal circumstances would be considered relatively undemanding of attentional resources. Current accounts, then, may not provide a complete explanation of HD patients' difficulty in carrying out more than one task simultaneously.

Our own studies raise the possibility of an alternative explanation. In a longitudinal study of cognition in early HD it was found that, contrary to expectation, the most sensitive markers of change were tasks with ostensibly low compared to high cognitive demands (Snowden, Craufurd, Griffiths, Thompson, & Neary, 2001). Thus, on the classical Stroop test (Stroop, 1935), the simple tasks of reading words aloud and naming colour blocks were more sensitive markers of cognitive change than the attentionally more demanding 'interference' task of naming the ink colour of incongruous colour words, requiring active allocation of attention and inhibition of a prepotent response. Similarly, the time taken to recite the months of the year was a sensitive marker of change, whereas the attentionally more demanding task of reciting the months of the year in reverse order was not. This seemingly counterintuitive pattern persisted across a number of tasks, suggesting an inverse relationship between sensitivity to change in HD and apparent cognitive demands. A cross-sectional, double-blind comparison of at-risk carriers and non carriers of the HD mutation revealed a similar pattern of results (Snowden, Craufurd, Thompson, & Neary, 2002). Carriers were impaired relative to non carriers on simple undemanding tasks, such as reading words on the Stroop, but not on more attentionally demanding tasks, such as the interference condition on the Stroop. A similar pattern was also reported by Bachoud–Lévi et al. (2001) and has since been reported by Ho et al. (2003), indicating that this is a robust observation.

If a fundamental deficit in HD is impaired attention, then one might have predicted greatest impairment on those tasks most demanding of attention, e.g. the interference and not the word-reading condition of the Stroop. How then can such apparently contrary findings be explained? The ability to carry out a task without attentional executive control is referred to as *automaticity* (Posner, 1978). Simple tasks, such as the Stroop word-reading condition and recitation of the months, involve the repetition of a limited number of responses or overlearnt routines, which under normal circumstances can be readily automatised. Healthy control subjects' efficiency in carrying out such tasks stems from their capacity to execute them as relatively automatic routines. If a primary deficit in HD lies in the capacity for automatising responses, then this would explain their disproportionate impairment on low-level tasks. HD patients would no longer derive the advantage, conferred to healthy control subjects, on low-level undemanding, compared to cognitively demanding tasks. It was therefore hypothesised that HD patients are impaired in the ability to implement automatic cognitive and motor routines (Snowden et al., 2001, 2002).

The notion that HD patients are impaired in the automatic execution of actions is in keeping with the theory proposed by Marsden (1982) that the basal ganglia play a critical role in the automatic implementation of learned motor programs. This hypothesis was based largely on physiological studies of patients with Parkinson's disease and it was not explicitly considered how the 'non-automatic' execution of motor programs might impact on attentional resources.

By definition, automaticity in a given task has been achieved once performance is minimally affected by other ongoing tasks (Logan, 1979). A corollary of this is that, if simple, repetitive tasks cannot be automatised, then they will *necessarily* place greater demands on conscious attention. The implication is that the impairment in 'attention', demonstrated so regularly in HD, may represent not so much a problem in allocation of attention or attentional set shifting *per se*, but a more fundamental impairment in the ability to 'automatise' behaviours, resulting in increased *demands* on patients' attentional resources.

The hypothesis is that impaired automaticity may contribute to the attentional problems observed in HD. Nevertheless, the interpretation of patients' poor dual-task performance in terms of impaired automaticity is currently inferential. A more direct demonstration of impaired automaticity would come from tasks that healthy controls are able to execute as efficiently when carried out simultaneously as in isolation. The performance of simultaneous, identical actions with both hands together would meet this criterion. In the present study we compared the performance of HD patients and controls on a simple finger-tapping task under single-task (unimanual) and dual-task (bimanual) conditions, adapting a procedure developed to study motor timing (Michon, 1967; Stevens, 1885). In this task, participants are required first to synchronise tapping movements with a metronome beat and thereafter to continue tapping at the same rate in the absence of auditory pacing cues. The task requires the production of repetitive responses yet makes minimal demands on movement sequencing, spatial accuracy and force modulation (O'Boyle, 1997). Moreover, the task is considered to be a 'low processing load' task, the performance of which has a negligible effect on other cognitive processes (Pashler, 1994). Indeed, among neurologically intact individuals, regularity of tapping rate is improved when tapping with two hands compared with one, a phenomenon termed the 'bimanual advantage' (Helmuth & Ivry, 1996). In such subjects, there is a strong spatial and temporal coupling of bimanual actions (Kelso, Putnam, & Goodman, 1983; Kelso, Southard, & Goodman, 1979). In keeping with this, there is a high degree of between-finger synchrony when carrying out the task with both hands (Helmuth & Ivry, 1996). As the tapping task has generally been used to study motor *timing*, we also included a control condition, in which auditory pacing cues remained present throughout the task, thus providing an external timing marker, allowing a direct comparison with unpaced performance, which is entirely dependent on an internal representation of time.

Table 1
Background clinical information for HD patients.

	Mean (SD)	Normal performance
UHDRS motor impairment score	21.3 (11.3)	1.1 (0.9)[a]
Total functional capacity/13	8.9 (1.9)	13 (0)[a]
Stroop: Colour-naming/total correct in 45 s	48 (15.2)	79.1 (14.0)[b]
Stroop: Word-reading/total correct in 45 s	65.7 (19.3)	108.2 (15.3)[b]
Stroop: Interference/total correct in 45 s	27.3 (8.9)	46.1 (10.4)[b]
Symbol-Digit Modalities Test/total correct in 90 s	29.5 (10.3)	60.9 (11.3)[b]
Total Verbal Fluency score	27.5 (10.9)	40.5 (10.7)[b]
MMSE/30	26.1 (2.7)	>24

[a] Normative data taken from Henley et al. (2008).
[b] Normative data taken from Paulsen et al. (2001).

Our hypothesis that HD involves an impairment in the automisation of simple, repetitive responses gives rise to the following predictions. First, variability in unimanual tapping performance, defined as the standard deviation of the mean inter-tap-interval, will be greater in HD patients than in controls and the degree of variability in HD should be similar for performance with and without external pacing cues. Second, variability in tapping performance will be further increased in HD, but not controls, in a bimanual 'dual-task' condition, in which a simultaneous identical action is executed with the contralateral hand. Third, when performing simultaneous bimanual actions, HD patients should show reduced bimanual coordination, defined as the degree of temporal 'lag' between responses, than healthy controls. Finally, if the findings have relevance beyond the motor domain then the degree of variability demonstrated on tapping should be correlated with performance on those simple cognitive tasks which have the potential to be executed automatically (i.e. the Stroop colour-naming and word-reading conditions), but not those that are more demanding of attention and executive control (i.e. the Stroop interference condition).

2. Methods

2.1. Participants

14 patients with clinically diagnosed and genetically confirmed Huntington's disease and 14 healthy controls took part in the study. The HD group consisted of 2 men and 12 women with a mean age of 49 (S.D. 10) who attended a multidisciplinary HD clinic. Patients were in the early stages of disease (4 in stage I, 8 in stage II) as designated by their scores on the Total Functional Capacity scale (Shoulson & Fahn, 1979). The mean illness duration was 4.1 years (S.D. 2.2). The control group consisted of 4 men and 10 women who were partners or friends of patients attending the clinic or volunteer hospital staff. Their mean age was 49 (S.D. 12) years, which did not differ significantly from that of the HD patients (t (26) = 0.73). All participants were right-handed according to self-report. The majority (11/14) of patients were taking established doses of psychiatric medication (e.g. Citalopram, Venlofaxine, Propranolol) to address the mood changes and/or agitation commonly observed in HD (Craufurd, Thompson, & Snowden, 2001) and two of these were taking neuroleptic medication (Quetiapine, Aripiprazole). None of the study participants were treated with medication to reduce chorea (e.g. Tetrabenazine). The study was approved by the local research ethics committee and all participants gave written informed consent in accordance with the Declaration of Helsinki.

2.2. Background clinical assessments

All patients were assessed using the Unified Huntington's Disease Rating Scale (UHDRS) (Huntington Study Group, 1996), which includes motor, functional and cognitive assessments. The UHDRS motor examination comprises standardised ratings of chorea, dystonia, occulomotor function, dysarthria, gait and postural stability. The total UHDRS motor score is the sum of individual items, yielding a maximum of 124, with higher scores indicating greater impairment. The HD Functional Capacity Scale (Shoulson & Fahn, 1979) rates the ability to engage in occupation, manage financial and domestic affairs and perform activities of daily living. The total functional capacity score (TFC) ranges from 0 to 13, with lower scores denoting greater functional impairment.

The UHDRS cognitive assessment includes the following tests:

i. Stroop Test (Stroop, 1935). The task consists of three conditions: naming colour blocks; reading colour words printed in black ink; naming the ink colour of incongruous colour words (interference condition). The score for each condition is the total number of correct responses (maximum 100) in 45 s.
ii. Symbol-Digit Modalities Test (Smith, 1973). The examinee is required to pair numbers with symbols according to a reference key. The score is the total number of correct written responses in 90 s.
iii. Verbal Fluency Test (Benton & Hamsher, 1989). The examinee is asked to generate as many words as possible beginning with a specified letter in 60 s. The score is the total number of words produced for three letters (F, A and S).

The Mini-Mental-State Examination (Folstein, Folstein, & McHugh, 1975) was administered as a measure of general cognitive function. Background clinical data are summarised in Table 1.

2.3. Apparatus

Data were collected using two custom-designed response boxes, measuring 85 × 145 mm. A touch-sensitive pad measuring 50 × 35 mm was mounted on each response box, placed centrally in the horizontal plane, with the upper edge 20 mm from the top of the response box. Presentation of auditory stimuli and response collection were controlled by E-Prime (Psychological Software Tools, Pittsburgh, PA) using a laptop computer running Windows XP.

2.4. Procedure

Participants were seated, with both forearms resting on a table upon which the response boxes were positioned equidistant from their midline. The participants were instructed to hold the response boxes between the thumb and fingers, leaving the index finger free to make flexion-extension movements onto the touch-sensitive pad. Whilst directing their gaze to a midline fixation point ('+') at eye-level, participants were required to synchronise finger taps with a series of tones (50 ms, 500 Hz) that occurred every 600 ms. In half of the trials ('unpaced') the tones were withdrawn following the 12th tone, after which participants were required to continue tapping at the same rate, until a further 30 responses had been collected. In the other half of trials ('paced') the 12 tones were followed by a further 30 tones, with which participants were required to continue synchronising their finger taps. At the start of each trial, participants were told whether the trial would be unpaced or paced. Unpaced and paced performance were both assessed unimanually (right-hand and left-hand individually) and bimanually (right and left hands simultaneously), resulting in a total of six trial types. At the end of the experimental session, participants were asked to verbally rate whether they had found the dual-task condition of comparable difficulty, easier or more difficult than the single-task condition.

2.5. Design

A practice session was completed in order to familiarise participants with the procedure. Each of the six trial types was repeated three times during the experimental procedure and was blocked as follows: (*a*) unpaced right-hand only, left-hand only, bimanual; (*b*) paced right-hand only, left-hand only, bimanual. The initial block of trials (unpaced or paced) was counterbalanced between participants, so the block order was either *a–b–a–b–a–b* or *b–a–b–a–b–a*.

2.6. Analysis

The principle variable of interest was *variability* in tapping rate, which was defined as the *standard deviation of the mean inter-tap-interval* for each individual trial. The mean and standard deviation of the inter-tap-interval for each trial type were calculated for each participant based on the final 30 responses from each trial, thus excluding responses collected during the initial 'pacing' tones. Inter-tap-intervals that were greater or less than 2.5 standard deviations from the run mean were subject to outlier screening. This resulted in the exclusion of 1.7% of responses made by HD patients and 1% of responses made by controls. In order to examine bimanual coordination, the time difference between responses produced with either hand was calculated (left minus right) and a mean 'lag score' was computed

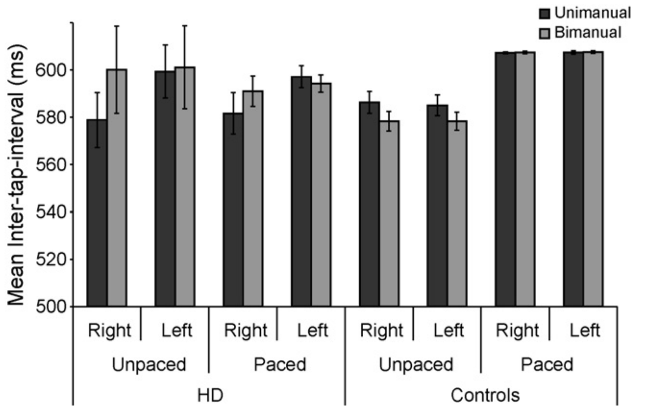

Fig. 1. Mean (±S.E.M.) inter-tap interval for unimanual and bimanual performance during unpaced and paced tapping.

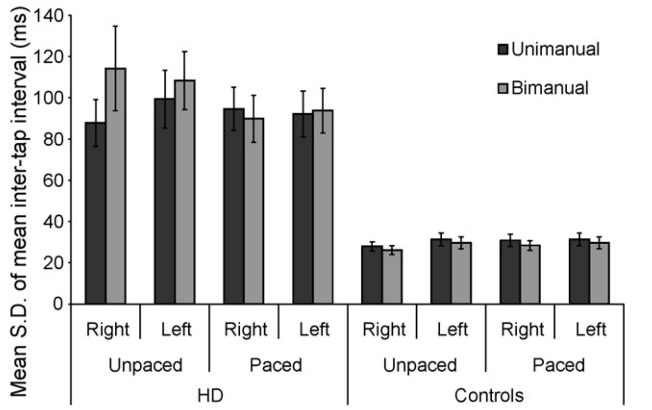

Fig. 2. Mean (±S.E.M.) tapping rate variability (mean S.D. of inter-tap-interval) for unimanual and bimanual performance during unpaced and paced tapping.

for each trial. An unsigned lag score was also computed, in which the direction of difference was ignored. Data were analysed using analysis of variance to examine effects of group (HD vs. controls) and condition (*Task*: single-task vs. dual-task, *Pacing*: unpaced vs. paced, *Hand*: right vs. left), and Pearson's correlation coefficients were computed to examine the relationship of tapping variability to motor, functional and cognitive measures of disease severity. In addition to the total UHDRS motor score we calculated a 'chorea score' (the sum of all clinical ratings of chorea) and an 'upper-limb bradykinesia' score (the sum of all clinical ratings of the speed and regularity of rapid finger taps and alternating hand movements).

3. Results

3.1. Tapping rate

Tapping rate (mean inter-tap interval) for each condition is displayed in Fig. 1. A Group (HD patients vs. controls) × Task (single-task vs. dual-task) × Pacing (unpaced vs. paced) × Hand (right vs. left) ANOVA was carried out to compare the tapping rate of HD patients and controls. There were no significant main effects. There were significant Hand × Group (F (1, 26) = 4.380, p = 0.046), Task × Hand (F(1,26) = 4.856, p = 0.037) and Task × Hand × Group (F (1,26) = 5.572, p = 0.026) interactions. There were no significant differences in tapping rate between the right- and left-hand but there was a trend towards more rapid performance in the right-hand for unpaced unimanual performance (t(13) = −2.066), p = 0.059). Unpaced tapping in controls was significantly faster under dual-task than single-task conditions for both right (t(13) = 2.945, p = 0.011) and left (t(13) = 2.877, p = 0.013) hands.

3.2. Variability in tapping rate

Fig. 2 illustrates variability of tapping rate (expressed as the S.D. of the mean inter-tap-interval) for each condition. A repeated measures Group (HD patients vs. Controls) × Task (single-task vs. dual task) × Pacing (unpaced vs. paced) × Hand (right vs. left) ANOVA revealed a main effect of Group (F (1, 26) = 27.672, p < 0.0001), indicating that HD patients demonstrated greater variability in tapping rate than controls. There were also significant Group × Task × Pacing × Hand (F (1, 26) = 9.955, p = 0.004) and Task × Pacing × Hand (F (1, 26) = 10.923, p = 0.003) interactions.

In order to explore the nature of the group interaction, separate Task × Pacing × Hand ANOVAs were carried out for each group. Within the control group there were significant main effects of Task (F (1, 13) = 6.008, p = 0.029), Pacing (F (1, 13) = 5.530, p = 0.035) and Hand (F (1, 13) = 7.227, p = 0.019). Controls showed reduced within-hand variability during dual-task performance than during single-task performance. They also showed less variability in tapping rate during unpaced tapping than during paced tapping, and for the right compared with left-hand. No significant main effects were observed in the HD group, but there was a significant Task × Pacing × Hand interaction (F (1, 13) = 11.428, p = 0.005). Paired t-tests revealed that HD patients showed significantly *greater* unpaced tapping variability for dual-task performance compared with single-task performance with the right-hand (t(13) = −2.219, p = 0.049). As can be seen in Fig. 2, there was also a numerical trend towards greater dual-task variability for both unpaced and paced performance with the left-hand but this did not reach statistical significance.

3.3. 'Dual-task' bimanual co-ordination

The mean between-hand lag for unpaced bimanual performance was −3.44 (S.D. 11.16) for HD patients and −1.76 (S.D. 9.51) for controls. For paced bimanual performance the mean between-hand lag was −1.30 (S.D. 13.88) for HD patients and −0.89 (S.D. 8.23) for controls. The data indicate an overall lead for the right-hand. As there is no a priori reason to expect one hand to lead consistently, we consider the mean unsigned between-hand lag data to be more meaningful. Fig. 3 shows the mean (S.E.M.) unsigned between-hand lag for unpaced and paced tapping. Repeated measures Group × Pacing ANOVA revealed a significant main effect of Group (F (1, 26) = 22.93, p < 0.0001), indicating a greater between-hand time lag in the HD group than in controls. There was no effect of pacing condition, indicating that the mean lag did not differ significantly between unpaced and paced conditions, and no interaction effect.

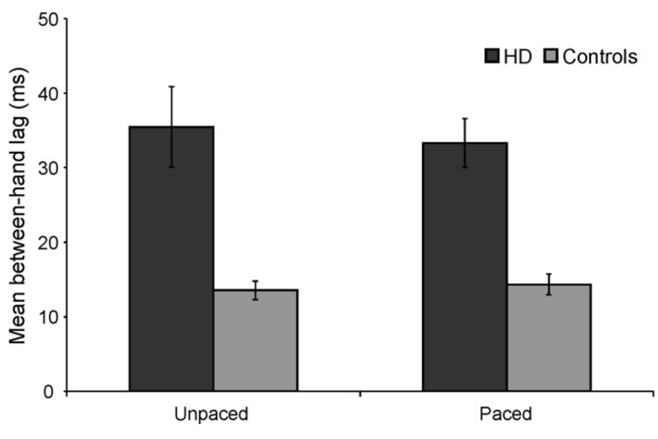

Fig. 3. Mean (±S.E.M.) between-hand lag (ms) for bimanual unpaced and paced tapping.

Table 2
Correlation of tapping variability (mean S.D. of inter-tap-interval) with motor, functional and cognitive measures (*$p<0.05$, **$p<0.005$, ***$p<0.001$).

	Unpaced				Paced			
	Unimanual		Bimanual		Unimanual		Bimanual	
	Right	Left	Right	Left	Right	Left	Right	Left
UHDRS motor	0.538*	0.564*	0.516	0.587*	0.625*	0.659*	0.689*	0.755**
UHDRS chorea	0.490	0.387	0.379	0.459	0.499	0.402	0.640*	0.592*
Upper limb bradykinesia	0.557*	0.485	0.437	0.436	0.682*	0.598*	0.528	0.545
Functional capacity	0.435	0.249	0.473	0.311	0.452	0.233	0.187	0.056
Stroop: Colour-naming	−0.575*	−0.750**	−0.568*	−0.620*	−0.580*	−0.751**	−0.625*	−0.758**
Stroop: Word-reading	−0.728***	−0.756**	−0.615*	−0.652*	−0.766***	−0.761**	−0.798***	−0.829***
Stroop: Interference	−0.36	−0.467	−0.345	−0.348	−0.224	−0.254	−0.173	−0.206
Symbol Digit test	−0.477	−0.586*	−0.448	−0.400	−0.43	−0.531	−0.524	−0.554*
Letter fluency (FAS)	−0.093	−0.254	−0.214	−0.229	−0.042	−0.226	−0.154	−0.175
MMSE	0.433	0.507	0.375	0.404	0.444	0.490	0.227	0.461

3.4. Subjective report of task difficulty

12/14 HD patients reported the dual-task condition to be more difficult than the single-task condition, compared with 1/14 control participants. This difference was statistically significant ($\chi^2 = 14.3$, $p < 0.0005$). 2/14 HD patients reported that the two conditions were of equal difficulty, compared with 11/14 control participants. None of the HD patients reported the bimanual condition to be easier, whereas two control participants did so.

3.5. Correlation of tapping variability with motor, functional and cognitive measures

Correlation coefficients between tapping variability and motor, functional and cognitive measures of disease severity are shown in Table 2. Tapping variability was most highly correlated with performance on the word-reading condition of the Stroop test, with significant correlations observed for all tapping conditions. Equally consistent but somewhat weaker correlations were observed between tapping variability and performance on the colour-naming condition of the Stroop test. There were no significant correlations between tapping variability and performance on the Stroop interference task or a verbal fluency task. Tapping variability was correlated with a clinical measure of motor impairment (UHDRS motor scale) for 7/8 experimental conditions, and with clinical measures of chorea and upper limb bradykinesia for 2/8 and 3/8 conditions respectively.

4. Discussion

We examined the hypothesis that individuals with HD are impaired in their capacity to automatise behaviour and that this may be an important factor in explaining their difficulty in executing more than one task simultaneously. That is, it may have relevance for understanding the deficits in attention so commonly reported in HD. We employed a simple motor tapping task that is thought to place minimal demands on attentional resources (Pashler, 1994). We argued that a lack of automaticity in HD would be manifest by greater response variability than in controls. More importantly, HD patients' performance should be adversely affected by a bimanual, 'dual-task' condition, whereas healthy controls should not.

The findings were in keeping with our predictions. Overall variability in tapping performance was significantly greater in HD patients than in controls. Variability was higher in HD in a dual-task (bimanual) compared to single-task (unimanual) condition for three of four relevant comparisons (right-hand unpaced, left-hand unpaced and paced). The opposite pattern was consistently observed in controls, who exhibited the bimanual performance advantage that has been reported previously (Helmuth & Ivry, 1996). Between-hand synchronisation during bimanual performance was significantly worse among HD patients than controls. Significantly more HD patients than controls reported the dual-task condition to be more difficult than the single-task condition.

Motor impairment is a core characteristic of HD. A natural question is whether the observed pattern of performance can be explained purely in terms of motor dysfunction. Chorea is the dominant characteristic of patients' movement disorder and might reasonably be expected to have an impact on accuracy and consistency of performance. This does not seem to provide an adequate explanation, since chorea was poorly correlated with tapping variability. Slowness in the initiation and execution of upper limb movements is a common clinical feature of HD (Thompson et al., 1988) and one which might be predicted to impact on tapping variability. However, a clinical rating of the speed and regularity of rapid finger taps and alternating hand movements did not correlate well with performance on the experimental tapping task. Tapping variability was moderately correlated with overall motor impairment, as measured by a clinical rating scale. However, these correlations were neither as strong nor consistent as those observed between tapping variability and performance on certain cognitive tasks. Moreover, there was no statistical difference in the mean tapping rate between HD patients and controls, precluding an explanation in terms of motor slowing. Thus, although motor impairment is likely to contribute to the observed variability in tapping performance, it does not appear to be a sufficient explanation of the data.

The tapping task we employed is a variant of a procedure commonly used to study motor timing (O'Boyle, 1997). The importance of timing for the optimal planning and coordination of movements has led to the hypothesis that impairment in cognitive timing functions could underlie the voluntary movement disorder in HD (Beste et al., 2007). Indeed, impaired tapping performance, demonstrated in both manifest (Freeman et al., 1996) and preclinical (Hinton et al., 2007) HD, has been attributed to a deficit in a cognitive timekeeping system. The question of whether there is a primary deficit in temporal processing in HD remains controversial. Studies have demonstrated that HD patients are impaired on tasks that require a time-dependent motor response, such as synchronising finger taps (Freeman et al., 1996) or gait (Bilney, Morris, Churchyard, Chiu, & Georgiou-Karistianis, 2004) to different frequencies, or the reproduction of specific temporal intervals (Beste et al., 2007). In contrast, there is little convincing evidence that non-motoric aspects of temporal processing are impaired in HD. In one study, HD patients were impaired relative to controls on a 2-alternative-forced-choice temporal identification task (Beste et al., 2007) but it should be noted that the task also placed significant demands on response selection and memory processes. Could our results be interpreted as reflecting impairment of a cognitive timekeeping system or hypothetical "internal clock"? A specific timekeeping deficit would predict greater mean variability for the unpaced condition, which is entirely dependent on an internal representation of a specific time interval, than in the paced condition, in which an external timing cue is available (Rao et al., 1997). In fact, HD patients demonstrated a similar magnitude of variability with and without external pacing cues (Fig. 2). Moreover, a general timing impairment would not account for the increased difficulty of bimanual compared to unimanual tapping among HD patients, as inferred from greater variability for bimanual tapping and the self-report of participants.

In control participants, tapping variability was significantly more variable in the left, non-dominant, hand across all conditions whereas in the HD group there was no significant difference between hands. Interestingly, a number of studies have demonstrated reduced left-sided striatal volume in HD (Mühlau et al., 2007; Rosas et al., 2001), which might potentially account for the observed lack of dominant-hand advantage in HD. However, given that asymmetry of neurological features is not commonly noted in HD this explanation is tentative.

Under normal circumstances, the production of simultaneous bimanual tapping movements would not be considered a dual-task. However, the increased subjective difficulty, greater variability and reduced between-hand synchrony observed amongst patients in the bimanual condition suggests that, for HD patients at least, it was. Whereas healthy controls were able to produce identical simultaneous movements with the two hands as easily (or better) than with a single hand, HD patients were unable to do so. For HD patients bimanual actions increased the task demands. As outlined in the introduction, we have previously demonstrated that simple rather than complex tasks are the most sensitive marker of cognitive change in manifest HD, and ascribed this finding to a failure of automaticity (Snowden et al., 2001), so that simple tasks, which under normal circumstances are amenable to automisation and therefore place minimal demands on conscious attention, make disproportionately high demands on attentional resources in HD. That such low-level tasks are a sensitive marker even in preclinical HD (Snowden et al., 2002) suggests that impaired automaticity may constitute a very early and fundamental feature of the condition. We argue that the present findings among HD patients of increased tapping variability compared to controls and increased variability for bimanual compared to unimanual tapping provide direct evidence of that lack of automaticity.

The notion that HD patients are impaired in the automisation of actions is consistent with the theory that the basal ganglia are responsible for the automatic execution of learned motor plans (Marsden, 1982). Supportive evidence for the role of the basal ganglia in the performance of overlearnt or automatised tasks comes from the functional neuroimaging literature. A number of studies have demonstrated that the shift from an effortful, controlled stage of skill learning to the highly practiced, automatic stage is associated with decreased activation of cortical areas, such as the dorsolateral pre-frontal cortex and anterior cingulate cortex, and increased activation of subcortical areas (e.g. Floyer-Lea & Matthews, 2004; Puttemans, Wenderoth, & S, 2005; Seitz & Roland, 1992; Wu, Chan, & Hallett, 2008). One of the regions most consistently reported to show increased activation during the performance of overlearnt, automatised actions is the putamen, which, in addition to the caudate nucleus is the primary site of pathology in HD (Vonsattel et al., 1985), in which atrophy can be detected a number of years before clinical onset of symptoms (Aylward et al., 2004).

These reports are of particular relevance to the present study because they explicitly highlight the link between attention and automaticity. Wu et al. (2008) noted a reduction in the importance of attention networks with the development of automaticity. A crucial question, for the present study, is whether the impaired automaticity demonstrated by the tapping tasks extends beyond the motor domain and has more general relevance for understanding of HD patients' cognition.

The pattern of correlations between tapping variability and neuropsychological test performance is revealing. Tapping variability was highly correlated with performance on the simplest word-reading condition of the Stroop test and, to a slightly lesser extent, the colour-naming condition of the Stroop test, but not with the interference condition of the Stroop or other neuropsychological measures. Thus, tapping variability correlated with performance on those simple neuropsychological tasks that have the potential to be executed automatically, but not with those that are demanding of voluntary attention and executive control. The word-reading and colour-naming conditions of the Stroop test share the same motor demands as the interference condition, indicating that the correlations cannot be explained in simple motor terms. Indeed, tapping variability correlated only moderately with measures of motor function in comparison to the very strong correlations between tapping variability and word-reading and colour-naming. The correlations support the view that impairments on the simple conditions of the Stroop test and on the tapping task reflect the same underlying deficit: namely, an impaired ability to automatise behaviour. That is, the same explanatory principle is applicable to cognitive and motor tasks.

Our findings from the study of finger-tapping performance in HD share similarities with the literature on gait in HD. People with HD show greater variability in footstep cadence than controls (Churchyard et al., 2001) and are impaired in synchronising footsteps with auditory cues (Thaut, Miltner, Lange, Hurt, & Hoemberg, 1999), tending to overestimate the required step frequency when cued to walk at a relatively slow pace (Bilney et al., 2004). This latter finding mirrors our own observation that people with HD tended to tap faster than the target speed during paced tapping, therefore not achieving 1:1 synchronisation between-finger taps and pacing cues. Another similarity between-finger tapping and gait in HD is the observation that gait parameters are perturbed when carrying out a secondary task (Delval et al., 2008). This finding is of particular relevance to the present study because it suggests that walking, ordinarily a highly automatised task, places demands on attentional resources in HD.

If HD patients are unable to automatise simple tasks due to striatal atrophy, then how are such tasks being executed? One might speculate that such tasks require the continued activation of those cortical attentional networks involved in skill learning. Indeed, there is increasing evidence of compensatory recruitment of cortical areas in HD during the performance of motor and cognitive tasks. In a PET study of paced finger opposition movements, Bartenstein et al. (1997) found that HD patients showed less activation of the striatum and its frontal motor projection areas than controls but greater activation of posterior cingulate and parietal areas. In a more recent study, Georgiou-Karistianis et al. (2007) reported increased recruitment of anterior cingulate, frontal, motor and parietal areas in HD compared with controls during performance of a Simon task of cognitive interference in which participants respond to either spatially congruent or incongruent stimulus-response mappings.

Impaired dual-task performance in HD (Delval et al., 2008; Sprengelmeyer et al., 1995) is typically interpreted as a fundamental problem in attention. The present data raise an alternative explanation or, at the very least, an additional contributory factor: failure of automaticity. If HD patients are unable to establish relatively automatised cognitive and motor routines, then simple tasks will place greater demands on conscious attention than under normal circumstances. At a neural level, this may involve the recruitment of additional cortical area to compensate for striatal degeneration (Bartenstein et al., 1997; Georgiou-Karistianis et al., 2007). If simple, repetitive tasks place significant demands on attentional networks then this has the potential to explain some of the attentional problems reported in HD. That is, observed deficits in attention may reflect increased *demands* on attentional resources, rather than the *allocation* of those resources or in *switching* of attention per se.

Impairment in the ability to automatise actions in HD might potentially account for other findings that appear counter-intuitive. In a dual-task study, involving peg placement and button pressing, Brown et al. (1993) found that the two tasks were not equally affected by a concurrent task. Whereas HD patients carried out a peg placement task equally well under dual and single-task conditions, performance on a button pressing task was compromised in the dual-task condition. That is, the apparently simpler, repetitive button pressing task was subject to more disruption than the peg placement task, which involved a more complex action and a higher degree of spatial accuracy and manual dexterity and, presumably, attention. A disorder of resource allocation could account for the impaired dual-task performance. However, there is no a priori reason why the peg placement task should be prioritised over the button pressing task. An interpretation, in line with that of Snowden et al. (2001, 2002), and the present study, is that, whereas the simpler task is executed relatively automatically by controls, so is minimally affected by a simultaneous task, it is attentionally demanding in HD patients so is disproportionately compromised by the competing task. The more complex, peg placement task, by contrast, would be relatively demanding of attention in both groups.

It is unlikely that there is a unitary explanation for the myriad of attentional deficits that have been reported in HD. Pathological changes are not confined to the basal ganglia (Mann, Oliver, & Snowden, 1993), and patients exhibit a range of executive impairments in keeping with frontal lobe dysfunction (Craufurd & Snowden, 2002). Nevertheless, the role of impaired automaticity warrants consideration. It would account for such clinical observations as the difficulty of HD patients in walking and talking simultaneously. Moreover, recognition that simple tasks place greater attentional demands on HD patients than they do in healthy individuals has practical implications for patients' clinical management and care. We do not underestimate the importance of core attentional processes, such as disengagement and shifting of attention, and resource allocation, in HD. Indeed, it is likely that a complex interaction exists between complementary attentional networks and processes. We suggest that impaired automaticity contributes to this process.

There is typically a clear separation in the HD literature between cognitive and motor components of patients' disorder. Yet, a failure of automaticity links the two. We would suggest that this aspect of basal ganglia function is a fundamental factor affecting both the motor function and cognition of HD.

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