ORIGINAL ARTICLE

Mind the gap: temporal discrimination and dystonia

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Background and purpose: One of the most widely studied perceptual measures of sensory dysfunction in dystonia is the temporal discrimination threshold (TDT) (the shortest interval at which subjects can perceive that there are two stimuli rather than one). However the elevated thresholds described may be due to a number of potential mechanisms as current paradigms test not only temporal discrimination but also extraneous sensory and decision-making parameters. In this study two paradigms designed to better quantify temporal processing are presented and a decision-making model is used to assess the influence of decision strategy.

Methods: 22 patients with cervical dystonia and 22 age-matched controls completed two tasks (i) temporal resolution (a randomized, automated version of existing TDT paradigms) and (ii) interval discrimination (rating the length of two consecutive intervals).

Results: In the temporal resolution task patients had delayed ($P = 0.021$) and more variable ($P = 0.013$) response times but equivalent discrimination thresholds. Modelling these effects suggested this was due to an increased perceptual decision boundary in dystonia with patients requiring greater evidence before committing to decisions ($P = 0.020$). Patient performance on the interval discrimination task was normal.

Conclusions: Our work suggests that previously observed abnormalities in TDT may not be due to a selective sensory deficit of temporal processing as decision-making itself is abnormal in cervical dystonia.

Introduction

Dystonia is a movement disorder characterized by abnormal postures due to involuntary muscle contractions. Individuals frequently use alleviating manoeuvres (sensory tricks) to reduce the severity of abnormal muscle activity [1] and the importance of such sensory influences has received much attention experimentally with a range of abnormalities in the sensory domain documented [2–4]. One of the most widely studied perceptual measures is the temporal discrimination threshold (TDT) which has been defined as the shortest interval at which subjects can perceive that there are two stimuli rather than one [5]. Elevated thresholds are present across subtypes of isolated dystonia [6]. Furthermore the finding that TDTs are abnormal in first-degree relatives of those with dystonia has led to the suggestion that the TDT represents an endophenotype. Correspondingly there has been much speculation on how mechanisms underpinning abnormal thresholds may inform on the pathogenesis of dystonia [6–9].

Interestingly current paradigms used to test the TDT not only assess temporal discrimination but also extraneous sensory and decision-making parameters. For example some studies test more than one sensory modality (visual, somatosensory) and deliver stimuli

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to two sites, which requires spatial integration (e.g. index and middle fingers). Also, the design of standard staircase methodology in which the separation between two stimuli is slowly increased or decreased in a predictable manner allows the obtained thresholds to be readily biased by a decision strategy unrelated to temporal discrimination ability. Elevated TDTs have been documented across a range of hypokinetic and hyperkinetic movement disorders, cerebellar disease and functional (psychogenic) symptoms [6,10–14]. Disease-specific abnormalities may be concealed within the currently used TDT metric and better quantification of the precise deficit could offer better insight into the pathophysiological mechanisms involved in these distinct diseases.

In the present study a more rigorous psychophysical methodology was applied and two tasks were tested which assessed different aspects of temporal processing in the millisecond range. A randomized and automatic version of the TDT, temporal resolution, had basic elements common to currently used TDT methods and removed potentially confounding elements which are not integral to the definition of resolution/acuity (the ability to detect that two stimuli are present rather than one). A second task, interval discrimination, examined the ability of subjects to compare the lengths of two consecutive intervals in the millisecond range. This task was designed to test a different aspect of time perception: temporal discrimination, i.e. the ability to discern differences in the lengths of two intervals. To each of these tasks an established mathematical model of decision-making was applied that can disentangle the quality of sensory evidence entering the decision from decision strategy and non-decision processes such as stimulus encoding and response execution. Each of these could potentially be abnormal in dystonia.

Methods

Twenty-two healthy subjects (mean age 56.2 years (±11.0), 17 females) and 22 subjects with cervical dystonia (mean age 58.2 years (±11.1), 17 females) were tested. All dystonic subjects had clinically apparent postural abnormality (rather than tremor dominant) and were receiving treatment with botulinum toxin injections (tested a minimum of 3 months after their last treatment). A full history and examination excluded subjects who had any evidence of significant cognitive disease, other major health problems or sensory problems in the limbs. Reasoning and intelligence were estimated by the non-verbal Raven matrix score (maximum/high performance score 12) [15]. The Toronto Western Spasmodic Torticollis Rating Score (TWSTRS, maximum/worst score 85) and disease duration were documented for all patients. Written informed consent was obtained and the study was approved by the local ethics committee.

Both tasks were performed seated and button presses were made using the index finger of the right hand. An answer was required for every trial even if uncertain of the answer and subjects were prompted to guess if they paused longer than 5 s (forced choice). Subjects were trained in each task (20 trials, data not analysed) prior to the start of each task. The total length of time of the experiment with both tasks was approximately 30 min. Experiments were coded in Matlab using the Cogent toolbox.

Temporal resolution task

Three hundred consecutive trials were presented in which subjects pressed a button with their right index finger to indicate whether they felt one or two stimuli (Fig. 1a). Unknown to participants, the proportion of single-stimulus trials was 30% and of double-stimulus trials was 70%. The double-stimulus trials had an entirely randomized interval range from 1 to 200 ms which could be any decimal within that range (generated using the random function in Matlab). The order of single and double trials was also randomized within the 300 trials. The index finger of the left hand was stimulated using a ring electrode connected in parallel with two Digitimer electrical stimulators (see Data S1 for further detail).

Interval discrimination task

After a short break, subjects were presented with 300 consecutive trials in which they were asked to respond with a button press whether the first or second interval was longer (Fig. 1b). One interval was selected from three fixed values (50, 100 and 200 ms). The other interval was randomized to be within the range from 1 ms up to twice the fixed value (100, 200 and 400 ms respectively). All stimuli were 2×200 μs square wave pulses delivered to the left index finger using a single Digitimer stimulator.

Psychometric analysis

Data were binned into 15 interval groupings spread evenly over the range of possible intervals and a psychometric function was fitted to response behaviour for each individual (equations are described in Data S1). For the temporal resolution task, the fitted curve describes how the tendency or probability to respond 'two pulses' rather than 'one pulse' increases with larger millisecond gaps between the two pulses (Fig. 2a, for examples in two patients). The floor of the function

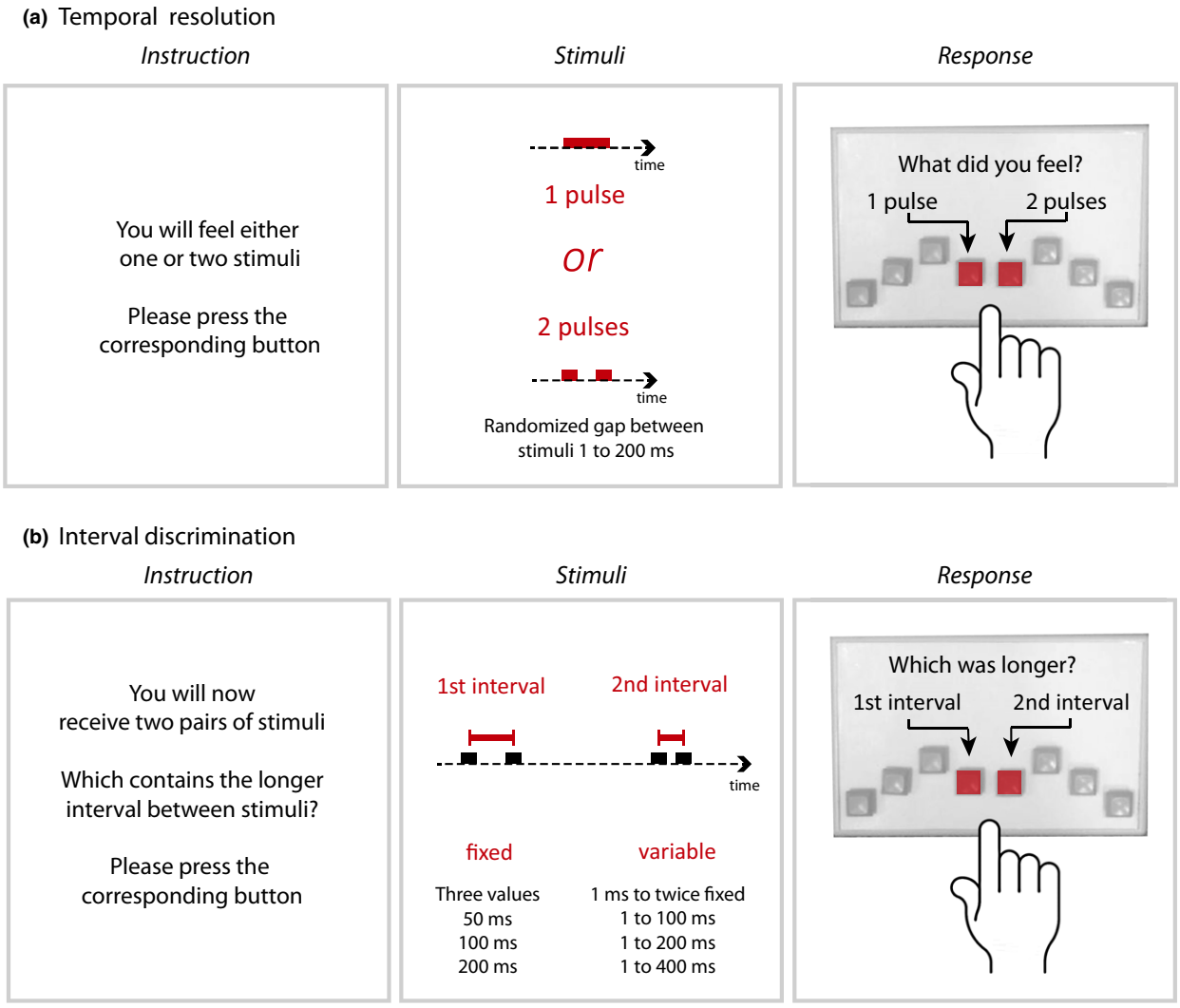


Figure 1 (a) Temporal resolution: 300 trials in which subjects respond with a button press whether they felt one or two stimuli. Either one pulse or two pulses (with an inter-stimulus range from 1 to 200 ms) were presented at each trial. (b) Interval discrimination: 300 trials in which subjects respond with a button press to indicate whether the first or second interval was longer. One interval was selected from three fixed values (50 ms, 100 ms and 200 ms) and the other interval varied within the range from 1 ms to twice the fixed value (100 ms, 200 ms and 400 ms respectively). [Colour figure can be viewed at wileyonlinelibrary.com].

was defined by the false positive rate. The temporal resolution threshold (T_{50}) was defined as the interval at which subjects responded 'two pulses' in half of the trials (probability of answering 'two pulses' is 0.5). Modelled thresholds are also given for temporal resolution at T_{75} and T_{98} in order to facilitate comparison to previous studies (probability of answering 'two stimuli' 0.75 and 0.98 respectively). The slope of the function at T_{50} was calculated as a measure of the range of time intervals over which decisions were uncertain. A similar psychometric analysis has recently been applied to the ascending staircase paradigm and the point of subjective equivalence corresponds to the T_{50} threshold [16].

For the interval discrimination task, a separate psychometric curve was fitted to the data for each of the three fixed intervals (50, 100, 200 ms), each containing a third of the trials. The interval discrimination threshold (I_{50}) indicated the variable interval at which the response probability for either answer was equal and the slope was calculated at this point (a steep slope reflecting high resolution for the discrimination of interval length). In the absence of bias, I_{50} would be identical to the fixed interval. To analyse all trials a contrast index (the difference between intervals divided by their total length, see Data S1) was used which accounts for the fact that a just-noticeable difference is longer for longer intervals (Weber's law [17]).

Drift diffusion model

Data from both tasks were fitted to the drift diffusion model which treats decision time as a period for weighing up information [18]. Mathematically, the distribution of reaction times and errors provides an estimate of the rate of information accumulation (drift rate), a decision boundary and non-decision time [19]. The basic assumption is that, in order to make a speeded choice between two options, evidence is accumulated sequentially over time during the decision period (Fig. 2b) [18]. As soon as sufficient evidence toward one option or the other has gathered, the process stops and a response is initiated. The accumulation process is governed by two distinct forces, the tendency to drift toward either decision boundary (drift rate) and a stochastic component (diffusion, i.e. random noise). The distance between the two boundaries (decision boundary) reflects the amount of evidence required before a decision is made. The non-decision time is the sum of all other processes involved such as the sensory encoding of stimuli and the time required for the motor execution of responses. Simultaneously fitting both choices and response times to the drift diffusion model allowed how individuals accumulate sensory information to be quantitatively dissociated from the critical amount of information they need before initiating a choice (analysis detailed in Data S1).

Statistical analysis

To compare distributions between groups, independent *t* tests were calculated when the data were normally distributed and the two-tailed Wilcoxon rank sum test for independent samples was used otherwise. The mean (±standard deviation) is given for descriptive statistics in the text. Repeated measures analysis of variance across condition was used to compare the drift rate between groups and the interaction of condition by group. Pearson's correlation was used to estimate the covariance of two variables. Data analysis and statistics were performed using Matlab (MathWorks Inc., Natick, MA, USA) and SPSS (IBM SPSS Stastitics, Armonk, NY, USA).

Results

There was no significant difference in age ($t(42) = -0.598$, $P = 0.838$) or sex (17 females in both groups) between groups which is important due to the known influence of both demographics on TDT values [20,21]. The mean TWSTRS score in the patient group was 35.9 (±11.9) and mean disease duration was 16.3 (±3.40) years. The mean Raven index in controls was 9.36 (±2.42) and cervical dystonia was 7.86 (±2.93) with no significant difference between the two groups ($t(42) = 1.83$, $P = 0.07$).

Temporal resolution

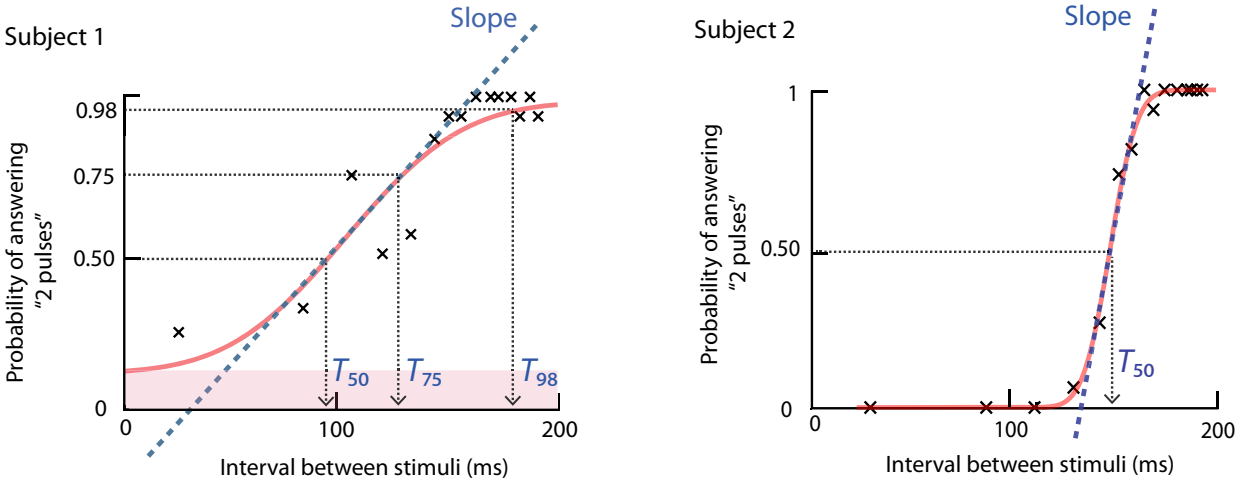
It was expected that subjects with cervical dystonia would demonstrate impaired performance in this task; however, performance across groups was found to be remarkably similar (Fig. 3a; individuals' data shown in Fig. S1). Temporal resolution thresholds (T_{50}, T_{75} and T_{98}) were comparable across groups and there was no significant difference in the slope gradient between controls and cervical dystonia. Therefore despite precise quantification of both isolated thresholds and slope metrics, no direct evidence was found that temporal resolution, the ability to detect two stimuli, based on accuracy data alone was impaired in cervical dystonia. In addition, summary metrics such as the hit rate (proportion of two-stimulus trials correctly identified) and false positive rate (the proportion of one-stimulus trials incorrectly identified as two-stimulus trials) were comparable between groups (Fig. 3a). Intelligence (estimated by the Raven matrix) strongly correlated with the slope (but not threshold) of psychometric function in both groups independently but also when the data were combined ($R^2 = 0.185$, $P = -0.004$). Thus a high intelligence score was associated with a steep slope corresponding to a small range of intervals over which there was decision uncertainty.

Subjects with cervical dystonia, however, were significantly slower and more variable in their response times (group mean of median reaction time in dystonia 1.07 s vs. 0.958 s in controls, $W_m = 396$, $P = 0.021$, $z = -2.31$; group mean of the standard deviation in dystonia 0.133 s vs. 0.234 s in controls, $W_m = 389$, $P = 0.013$, $z = -2.47$) (Fig. 3b). This suggested that despite data of comparable accuracy there was a systematic alteration in the timing of responses in dystonic subjects with the longest reaction times seen for the more difficult decisions (Fig. 3c).

In order to obtain more insight into this observation the drift diffusion model was used which synergistically evaluates accuracy and reaction time data in order to quantify separate decision-making components. Given reports that motor function of the limb can be altered in cervical dystonia [22] it was important to show that non-decision time was equivalent between groups (median in patients 0.880 s vs. 0.782 s in controls, ns) (Fig. 4a). This value is an estimate of the minimum reaction time that would be present even if perceptual discrimination were instantaneous.

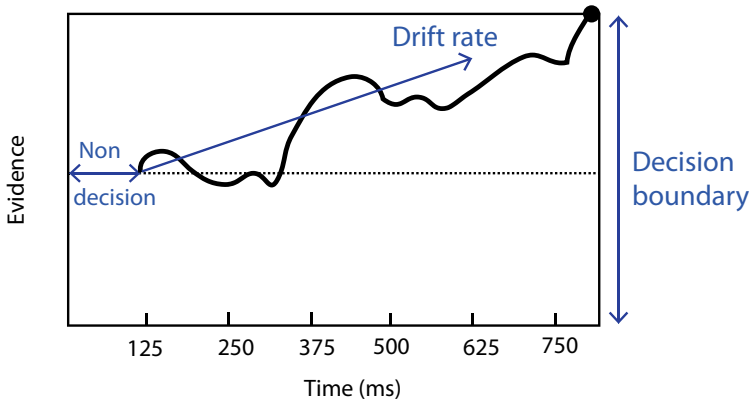
(a) Psychometric analysis

Symbol	*Parameter*	*Interpretation*
T_{50}	0.50 threshold	Sensitivity measure at different levels of response certainty
T_{75}	0.75 threshold	
T_{98}	0.98 threshold	
-	0.50 slope	Acuity/range of parameter over which decision difficult



(b) Drift diffusion model

Parameter	*Interpretation*
Non-decision time	Sum of all other processes involved (sensory encoding, motor execution of response)
Drift rate	Quality of stimulus, amount of input information
Decision boundary	Criterion setting/speed-accuracy trade off



It is therefore unlikely that increased reaction times observed in dystonia patients were an artefact due to the increased time needed to execute the motor response required for the button press. As expected, drift rate significantly varied across interval bins (df = 3.23, $F = 12.7$, $P = 0.001$), with lowest drift rates for difficult decisions, close to the perceptual limit. However, there was no difference in the drift rates between patients and controls (df = 3.23, $F = 1.60$, $P = 0.191$), indicating that the quality of the information on which decisions were based was not significantly different between groups (Fig. 4b). In contrast, patients had an elevated decision boundary (median in cervical dystonia 0.560 vs. 0.293 in

Figure 2 (a) Example of psychometric analysis. Each graph plots actual data and a fitted curve from two patients performing the temporal resolution task. Data were binned into 15 interval ranges and the proportion of trials to which subjects answered 'two pulses' is marked by crosses. Response behaviour was modelled using the psychometric function (solid line). The temporal resolution threshold (T_{50}) was defined as the interval at which subjects answer 'two pulses' in half of the trials. The slope of the function at T_{50} is a measure of the range of intervals of decision uncertainty. Threshold values and slope metrics are complementary when evaluating discrimination performance. For example, it can be seen that subject 1 had a relatively high false positive rate (floor of function accentuated by shaded region), T_{50} is approximately 95 ms and the slope is relatively shallow. Subject 2 by comparison had a low false positive rate, the threshold (T_{50}) was greater and the slope is steeper reflecting more consistent responses [with a high slope value (slope = $\Delta y/\Delta x$)]. (b) Drift diffusion model. The model simultaneously analyses reaction time and accuracy data. In order to make a speeded choice between two options, evidence accumulates over the decision period. When sufficient evidence for one of the two options has gathered, a decision is made and a response initiated. Two distinct components drive the accumulator: a tendency to drift toward the correct choice (drift rate) and a random component (diffusion). An example graphical representation of the drift diffusion process is shown by the curved line and indicates the amount of evidence for the 'upper' response as it evolves over time. At about 800 ms the upper boundary is crossed and the process ends. [Colour figure can be viewed at wileyonlinelibrary.com].

controls, $W_m = 348$, $P = 0.020$, $z = 2.33$) (Fig. 4c). This suggested that dystonic patients had set a different decision criterion, requiring greater evidence before committing to a decision.

Interval discrimination

The second task evaluated the ability to discriminate the length of intervals between successive pairs of stimuli. Subjects reported that this task was more difficult than the temporal resolution task, with one control and two dystonic subjects being unable to complete the task ($n = 41$). The psychometric function was fitted for each of the fixed intervals (50, 100 or 200 ms, Fig. S2a). No clear group difference in response accuracy was observed, with comparable I_{50} and slope metrics at each fixed interval (Fig. S2b). Response behaviour using the contrast index to combine trials was thus similar across groups (Fig. S3a). Compared to controls, subjects with cervical dystonia showed a trend to longer responding for the task but this was not significantly different between groups in terms of the mean of the median (dystonia 2.42 s vs. 2.31 s in controls, $W_m = 492$, $P = 0.061$, $z = 1.87$) or variability (mean of standard deviation in dystonia 0.399 s vs. 0.469 s in controls, $W_m = 484$, $P = 0.097$, $z = 1.65$) (Fig. S3b). Similar to the temporal resolution threshold, it was decisions around the perceptual threshold (more difficult decisions with lower accuracy) which had the most pronounced increase in reaction time in dystonia (Fig. S3c).

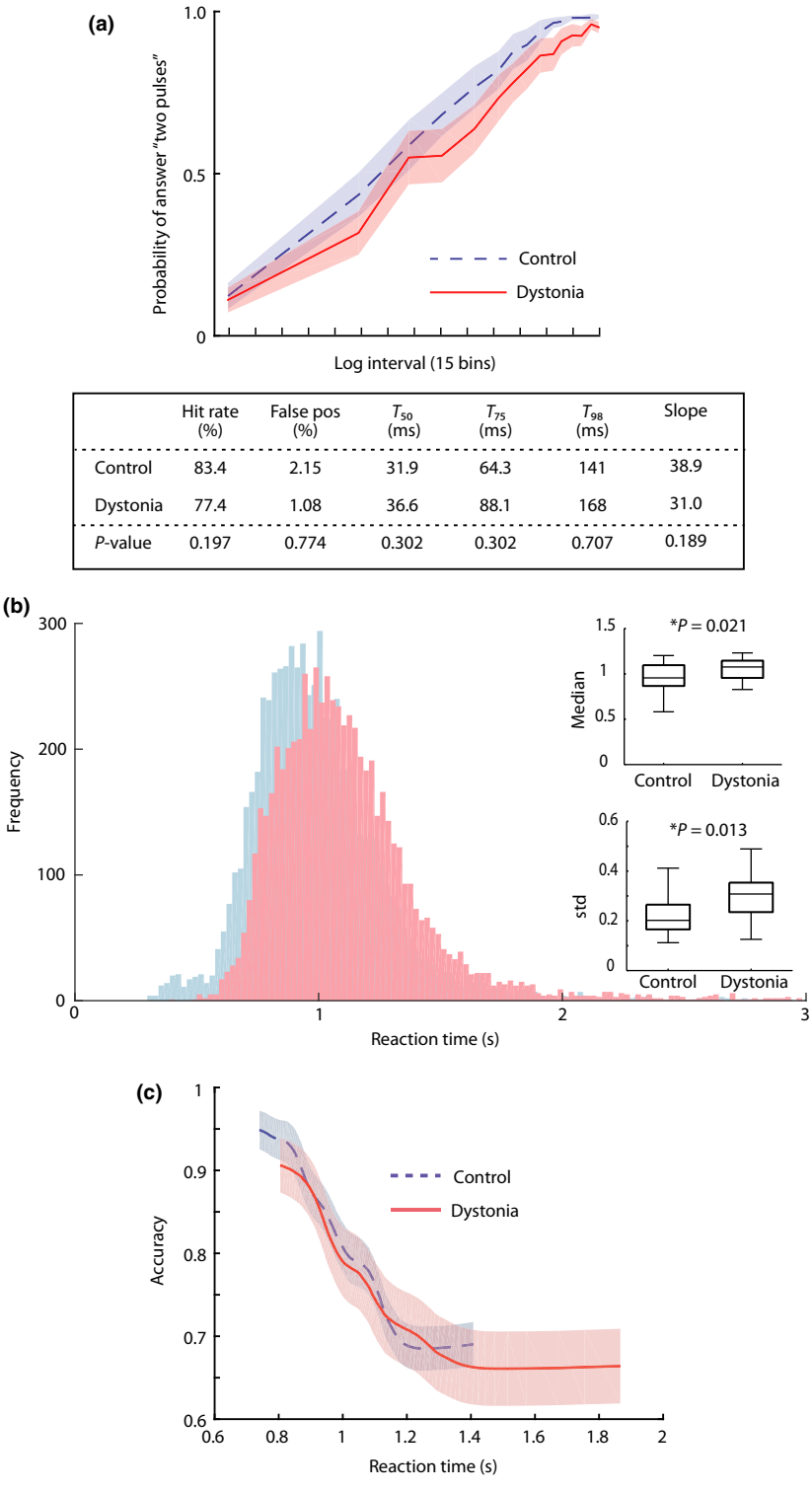
Modelling data from the interval discrimination task using the drift diffusion model again found no difference in the non-decision time between groups ($W_m = 366$, $P = 0.672$, $z = 0.424$). Diffusion rates were lower than in the temporal resolution task, in keeping with this task being more difficult due to decreased quality of sensory information available. As expected, the drift rate approximated zero when there was no contrast between the two intervals and increased with contrast magnitude (Fig. S3d, df = 2.78, $F = 13.3$, $P < 0.001$) and there were no group differences (interaction of group and drift rate df = 2.78, $F = 1.05$, $P = 0.397$) suggesting that the quality of sensory information available for the task was equal in both groups. In this task, the decision boundary was not significantly different (dystonia $a = 0.637$ vs. $a = 0.535$ in controls, $W_m = 316$, $P = 0.313$, $z = -1.01$).

Relationship between tasks

Across individuals the slope in the temporal resolution task correlated strongly with the slopes in the interval discrimination task; as such both tasks appear to sensitively test a common aspect of sensory processing ability (Fig. S4).

Discussion

Two tasks designed to better quantify temporal processing in dystonia are presented. The first task was similar to existing TDT paradigms but the order of stimuli presentation was randomized rather than incremental. This simple paradigm shift revealed no significant difference between patients and controls in their accuracy in discriminating single from double stimuli. However, due to the observation that patients showed longer and more variable reaction times, reaction time and accuracy data were combined into a decision-making model. This demonstrated that patients approached decision-making differently to controls with a higher criterion for information (decision boundary). A further task investigating the ability to distinguish intervals presented in pairs found patients to be no worse at interval discrimination. Our data show that altered decision-making is likely to influence threshold values and questions the assumption that abnormal TDT thresholds in



	Hit rate (%)	False pos (%)	T_{50} (ms)	T_{75} (ms)	T_{98} (ms)	Slope
Control	83.4	2.15	31.9	64.3	141	38.9
Dystonia	77.4	1.08	36.6	88.1	168	31.0
P-value	0.197	0.774	0.302	0.302	0.707	0.189

Figure 3 Temporal resolution. (a) Psychometric analysis. Line plot of the probability of answer 'two pulses' (*y*-axis) and log(inter-stimulus interval) (*x*-axis). Mean control (blue, dotted line) and dystonia (red, solid line) with shaded standard error. There was little difference in response behaviour across the range of intervals tested. Group metrics: hit rate (the percentage of two-stimulus trials in which subjects correctly identified an interval) and false positive rate (false pos, the percentage of trials where only one stimulus was delivered in which subjects incorrectly identified an interval) were calculated. Modelled thresholds are given for temporal resolution at T_{50}, T_{75} and T_{98} in order to facilitate comparison to previous studies. The slope at T_{50} has the units probability of response/ms. The *P* value from the Wilcoxon rank sum test for independent samples is given on the lower row of the table for each variable. Subjects with dystonia had a trend for increased thresholds compared to controls at both the T_{75} and T_{98} level, but neither was significantly different. (b) Reaction time histograms of all trials (200 bins) revealed systematic differences in the distribution of reaction times. Both mean median reaction time and mean standard deviation of variance were elevated in the dystonic group. (c) Plotting accuracy against reaction time (10 bins) revealed a systematic difference in the manner in which dystonic subjects responded. [Colour figure can be viewed at wileyonlinelibrary.com].

dystonia are solely due to impaired temporal discrimination.

Superficially, documenting TDT is a simple procedure. It can be defined as the shortest interval at which subjects can perceive that there is a gap between two stimuli. Each trial represents a choice between two options in which the participant must communicate whether they perceived one or two stimuli. During an experiment the interval between two stimuli is varied and the threshold at which they

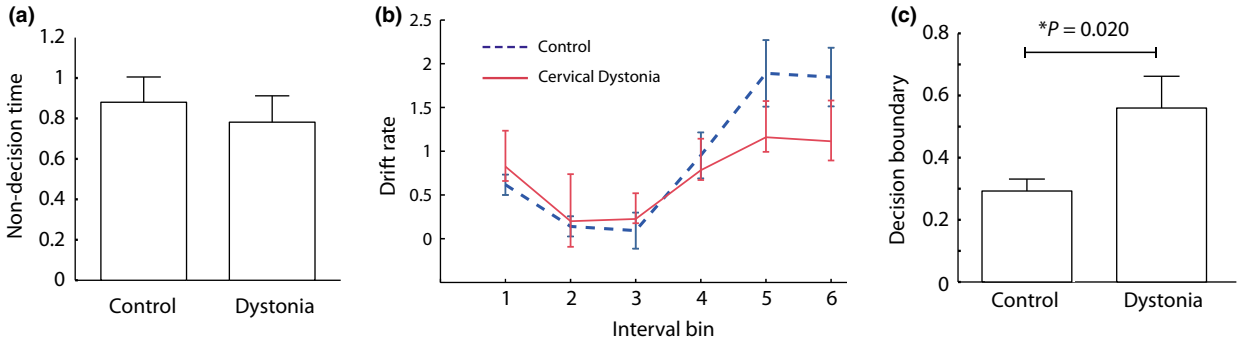


Figure 4 Drift diffusion model. (a) Non-decision time was no different between groups (bar plot, error bars display standard error). (b) Drift rate, a marker of the quality of sensory information, significantly varied across interval bins. As 30% of trials comprised the 0 ms bin there are six conditions in the model output (bin centres 0 ms, 13 ms, 44 ms, 85 ms, 122 ms, 158 ms). Difficult decisions, close to the perceptual limit, had low drift rate (bins 2 and 3). The lack of significant difference between groups suggests that there is no significant difference in the quality of sensory information reaching the decision process in cervical dystonia. (c) The decision threshold was increased in cervical dystonia suggesting that patients required greater evidence before a decision was made. [Colour figure can be viewed at wileyonlinelibrary.com].

detect this gap is noted. Ascending and descending staircase designs, in which the interval between stimuli is systematically increased or decreased, have shown similar results in many studies in the literature.

However, in the psychophysical literature it is well known that such predictable threshold paradigms are vulnerable to the influence of multiple decision-making parameters [17]. These can be collectively referred to as the participant's decision criterion and are determined by factors such as instruction, payoffs and reward contingencies [23]. Furthermore in some previous studies (fuelled by a genuine desire for greater sensitivity and specificity) complicating and confounding components have been incorporated into the TDT. For example some tasks introduce an obvious spatial element (two stimuli delivered at distinct locations), test both the somatosensory and visual modality, use single-stimulus trials that may not be true catch trials (recognizable by being of weaker intensity) and have up to four possible response options which recruits more complex decision-making [6,7,24].

For these reasons our first task, temporal resolution, was a randomized and automated version of commonly used TDT protocols which aimed to minimize both the effects of bias and potentially confounding elements. The second task required comparison of two consecutive interval lengths, a further test of temporal discrimination inspired by our current nomenclature of the psychophysical deficit in dystonia 'temporal discrimination threshold'. In addition for the first time both accuracy and reaction time were recorded, since modelling these data in synergy allows assessment of these previously unexplored components of the decision-making process.

Interestingly, clear evidence could not be provided for the existence of deficits in temporal discrimination in cervical dystonia in either task. In the temporal resolution task patients and controls were equally able to classify one- versus two-stimulus trials. Furthermore the ability to compare the length of two consecutive intervals, interval discrimination, was comparable between groups. Patients were slower in their responses, however, and demonstrated greater intra-subject variability in response time in the temporal resolution task. Such an increase in response time could reflect either slower sensory processing or a higher threshold for initiating a response. The data were therefore modelled using the drift diffusion model which evaluates response and response time in order to quantify separate decision-making components. The model confirmed our psychometric results with equivalent drift rates between groups (no difference in the quality of sensory information upon which decisions were based). In the temporal resolution task the decision boundary (the level of evidence required before a decision is made), even when the paradigm was randomized, was the key difference between groups. As such, in a task with the same components as commonly used TDT tasks, dystonic subjects set a more conservative decision-making strategy (despite the forced choice and randomized design).

Interestingly, an increase in decision boundary could contribute to elevated thresholds obtained using an ascending staircase design (a popular method used in some but not all previous TDT publications in dystonia). An increased decision boundary translates into a bias for subjects to wait before a greater amount of sensory evidence is available before reporting a change in stimuli. Doubt about whether two stimuli were

presented on trial n will tend to favour postponing the decision to trial $n + 1$. These effects are seen irrespective of the quality of the sensory signal. Thus our result does not query the reliability of previous studies in which a large body of evidence points to differences in performance in psychophysical tests in dystonia. However, our results do offer an alternative interpretation of the TDT as a consistent bias in the form of increased boundary separation, and altered decision-making in dystonia could partially explain some previous results.

Our results may also offer a tentative link to work which has started to identify subtle cognitive and behavioural problems in association with dystonia [25]. For example, anxiety and depression have been documented in over 50% of patients in some studies [26]. It has not yet been fully elucidated which of these are primary features of dystonia and which may be a consequence of the motor impairment [25]. However, any such change can potentially influence performance on psychophysical tasks. For example, anxiety can lead to an increase in the decision boundary in a similar manner to the change observed in cervical dystonia [18]. Our work therefore identifies the need to evaluate psychophysical performance within models that also evaluate psychological comorbidities and cognition in parallel.

It is important to consider differences between our paradigm and traditional methods. For example stimuli were delivered at a single site; it is possible that the spatial integration required to define two-stimulus trials delivered at different sites (seen in some but not all paradigms) is the core problem in cervical dystonia (any spatial computation is inherently more complex in cervical dystonia due to abnormal head and neck position). Another important difference is that the order of stimulus presentation was randomized. An alternative hypothesis is that threshold abnormalities observed with ordered staircase paradigms are actually testing the ability of subjects to detect a change in stimuli rather than temporal discrimination. In line with this argument we have recently shown that mismatch negativity, an electroencephalogram event calculated by subtracting the potential produced by a standard repeated stimulus from that produced by a rare 'oddball' stimulus, correlated with TDT obtained by staircase methodology in cervical dystonia. Higher thresholds on the TDT were associated with smaller mismatch negativity thresholds, both suggesting that the saliency of change was reduced (J-.C. Chen, R. Feng, A. Sadnicka, et al., unpublished data).

The fact that such a simple paradigm change can reveal so many unanswered questions emphasizes the complexity of understanding the significance of sensory deficits in dystonia. Abnormalities in the detection of stimuli relating to timing, spatial representations, pain, thermal qualities and kinaesthesia have all been documented [3]. This hints that there may be a common mechanism central to how subjects with dystonia perceive and report sensory phenomena at the root of all of these deficits; however, the nature of this mechanism remains poorly defined. In this specific task a change in a core decision-making parameter has been shown but it remains to be established whether a more fundamental component of sensory processing is at the root of other sensory deficits. As the neural correlates to psychophysical phenomena are increasingly understood, there is a growing need to better define the precise psychophysical deficit in dystonia so that the true neurobiological significance can be better appreciated [27,28].

This study has attempted to test as purely as possible perceptual sensitivity for millisecond timing mechanisms and assess the contribution of decision-making components. However, the detailed characterization of psychophysical performance requires careful interpretation, and our results need validation with further studies in this patient group and their relatives (to examine endophenotype phenomena). For example, there was a trend for drift rate to be reduced in the temporal resolution task at longer interval bins and as such our study may have been underpowered to detect subtler abnormalities in sensory processing which could coexist together with the shift in the decision boundary observed.

It is relatively recently that the sensory aspects of movement disorders have been championed and their importance in pathogenesis debated. Abnormalities in various domains of sensory processing have been documented in almost all movement disorders; yet how such abnormalities interact to cause the distinct movement disorders are still far from being defined. It is hoped that the application of novel methods and analysis, such as those detailed in this study, will provide better tools to identify disease-specific abnormalities in the sensory domain with ensuing insight into the pathophysiology of dystonia and other movement disorders.

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Disclosure of conflicts of interest

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Individual data for temporal resolution task.
Figure S2. Interval discrimination data subdivided by fixed interval.
Figure S3. Interval discrimination group data.
Figure S4. Sensitivity of tasks.
Data S1. Methods.

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