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Research Report

# Language disorders in patients with striatal lesions: Deciphering the role of the striatum in language performance



Q5  
Q4 Lorna Le Stanc<sup>a,b,c,d</sup>, Katia Youssou<sup>a,b,c,e</sup>, Maria Giavazzi<sup>a,b,c</sup>, Agnès Sliwinski<sup>a,b,c,e</sup>, Anne-Catherine Bachoud-Lévi<sup>a,b,c,e</sup> and Charlotte Jacquemot<sup>a,b,c,\*</sup>

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## ABSTRACT

The classical neural model of language refers to a cortical network involving frontal, parietal and temporal regions. However, patients with subcortical lesions of the striatum have language difficulties. We investigated whether the striatum is directly involved in language or whether its role in decision-making has an indirect effect on language performance, by testing carriers of Huntington's disease (HD) mutations and controls. HD is a genetic neurodegenerative disease primarily affecting the striatum and causing language disorders. We asked carriers of the HD mutation in the premanifest (before clinical diagnosis) and early disease stages, and controls to perform two discrimination tasks, one involving linguistic and the other non-linguistic stimuli. We used the hierarchical drift diffusion model (HDDM) to analyze the participants' responses and to assess the decision and non-decision parameters separately. We hypothesized that any language deficits related to decision-making impairments would be reflected in the decision parameters of linguistic and non-linguistic tasks. We also assessed the relative contributions of both HDDM decision and non-decision parameters to the participants' behavioral data (response time and discriminability). Finally, we investigated whether the decision and non-decision parameters of the HDDM were correlated with brain atrophy.

The HDDM analysis showed that patients with early HD have impaired decision parameters relative to controls, regardless of the task. In both tasks, decision parameters better explained the variance of response time and discriminability performance than non-

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1 decision parameters. In the linguistic task, decision parameters were positively correlated 66  
2 with gray matter volume in the ventral striatum and putamen, whereas non-decision 67  
3 parameters were not. 68

4 Language impairment in patients with striatal atrophy is better explained by a deficit of 69  
5 decision-making than by a deficit of core linguistic processing. These results suggest that 70  
6 the striatum is involved in language through the modulation of decision-making, pre- 71  
7 sumably by regulating the process of choice between linguistic alternatives. 72  
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## 15 1. Introduction 16

17 Since the turn of the century, neurofunctional models of 18  
19 language have been evolving and converging on a consensus 20  
21 that language recruits a network of frontal, temporal and 22  
23 parietal regions that is left-lateralized in most individuals (Ben 24  
25 Shalom & Poeppel, 2008; Fedorenko & Thompson-Schill, 2014; 26  
27 Indefrey & Levelt, 2004; Jacquemot et al., 2003). Neuroana- 28  
29 tomical connectivity studies have shown that these regions 30  
31 are connected via lexical ventral and articulatory- 32  
33 phonological-syntactic dorsal pathways (Catani et al., 2005; 34  
35 Poeppel et al., 2012; Scott & Johnsrude, 2003; Tomasi & 36  
37 Volkow, 2012). However, these models do not include sub- 38  
39 cortical structure whereas neuropsychological literature on 40  
41 patients with subcortical lesion and associated language dis- 42  
43 orders tends to challenge these models (see Birba et al., 2017; 44  
45 Jacquemot & Bachoud-Lévi, 2021a). A open issue is whether 46  
47 subcortical structures should be integrated neurofunctional 48  
49 models of language. 50

51 Indeed, all the areas comprising the identified network are 52  
53 cortical, but clinical studies of patients with subcortical lesions 54  
55 and imaging studies have raised questions about the possibility 56  
57 of subcortical regions also being involved in the language 58  
59 network. Studies on dysarthria in patients with subcortical 60  
61 lesions—particularly lesions of the striatum, as observed in 62  
63 Parkinson's disease and Huntington's disease (HD)—have 64  
65 revealed a role for the striatum in speech motor control 66  
67 (Ackermann & Ziegler, 1991; Giraud et al., 2008; Riad et al., 2020; 68  
69 Whitfield & Goberman, 2017). Other disorders or lesions of the 70  
71 striatum lead to subcortical aphasia, which is characterized by 72  
73 anomia, reduced word fluency, perseveration, semantic in- 74  
75 consistencies and semantic and morphological paraphasia 76  
77 (e.g., *utile* “useful” eliciting *desinutile* “non-useless” with a 78  
79 duplication of negative affixations) (Cambier et al., 1979; Cappa 80  
81 et al., 1983; Gil Robles et al., 2005). These language deficits are 82  
83 generally detected in complex and demanding language tasks 84  
85 requiring a high level of language control or syntax re-analysis 86  
87 (Abutalebi et al., 2000; Friederici & Kotz, 2003a; Jacquemot & 88  
89 Bachoud-Lévi, 2021b; Kotz et al., 2003). However, it is difficult 90  
91 to assess subcortical language symptoms, and additional 92  
93 cortical or white matter lesions cannot be excluded in many 94  
95 cases (Radanovic & Mansur, 2017). Furthermore, striatal dam- 96  
97 age does not always cause typical aphasic symptoms (Nadeau 98  
99 & Crosson, 1997) and can mostly be attributed to cortical 100  
101 hypoperfusion (Hillis et al., 2002). 102

103 HD is an inherited basal ganglia disorder. It is unique 104  
105 among subcortical disorders in that it provides us with access 106  
107 to a genetic model of striatal injury. It also provides opportu- 108  
109 nities for identifying and analyzing homogeneous groups of 110  
111 patients with striatal lesions, as opposed to the single cases 112  
113 studied for other subcortical disorders, including stroke. HD is 114  
115 an inherited neurodegenerative disease caused by the 116  
117 expansion of CAG triplet repeats in the gene encoding hun- 118  
119 tingtin, resulting in the production of an abnormal huntingtin 120  
121 protein. Degeneration can be observed in the brain, principally 122  
123 in the striatum, long before clinical diagnosis (Douaud et al., 124  
125 2006; Pini et al., 2020; Tabrizi et al., 2011; Vonsattel et al., 126  
127 1985). The presence of the causal gene mutation can be 128  
129 detected by genetic tests before the development of symp- 130  
131 toms in so-called “premanifest” mutation carriers. Clinical 132  
133 diagnosis, based on an evaluation of motor symptoms with 134  
135 the Unified Huntington's Disease Rating Scale (UHDRS), is 136  
137 generally made when patients are in their fourth or fifth 138  
139 decade of life (Huntington Study Group, 1996; Ross et al., 2019; 140  
141 Shoulson, 1981). However, this motor diagnosis may be pre- 142  
143 ceded by cognitive disorders. 144

145 Language disorders can be detected as early as the pre- 146  
147 manifest stage of HD (Hinzen et al., 2018; Nemeth et al., 2012; 148  
149 Riad et al., 2020; Rusz et al., 2014). At later stages, all compo- 150  
151 nents of language are impaired. HD patients have phonolog- 152  
153 ical (processing of speech sounds) difficulties recognizing 154  
155 phonemes within sentences (Teichmann et al., 2009). They 156  
157 also have morphological (combination of sounds to form 158  
159 words) impairment in the domain of verbal and nominal in- 160  
161 flection, with difficulties in verb-conjugation tasks and tasks 162  
163 assessing alternations between the masculine/feminine 164  
165 forms of adjectives (Giavazzi, Daland, Palminteri, Peperkamp, 166  
167 Brugières, et al., 2018; Longworth, 2005; Németh et al., 2012; 168  
169 Teichmann et al., 2005, 2008b; Ullman et al., 1997). Syntacti- 170  
171 cally (combination of words into sentences), HD patients find 172  
173 it harder to understand passive sentences than active sen- 174  
175 tences and have difficulties processing the syntactic rela- 176  
177 tionship between coreferential expressions in sentences (Illes, 178  
179 1989; Sambin et al., 2012; Teichmann et al., 2005, 2008a). In 180  
181 semantic tasks (relating to the meaning of words and sen- 182  
183 tences), HD patients have difficulty understanding idioms 184  
185 correctly (Teichmann, Dupoux, et al., 2008). Pragmatically (use 186  
187 of context to interpret meaning), they find it difficult to use 188  
189 referential items to identify story characters and objects and 190  
191 to establish the topics discussed (Hinzen et al., 2018). 192

There is growing evidence for language deficits in HD patients, but the origin of these problems has yet to be determined. In many studies, HD patients and premanifest mutation carriers were asked to produce or choose between linguistic alternatives (masculine/feminine forms, conjugation forms, syntax trees, etc.). All of these tasks require decision-making processes, which take place in the frontostriatal network (Palminteri et al., 2012; Robbe & Dudman, 2020). Any deficit of these processes can affect language performance, particularly in linguistic tasks involving a decision between alternatives. In such cases, the language impairment of HD patients would result from a decision-making defect that would also be expected to affect non-linguistic processing, rather than a language-processing deficit *per se*.

It, thus, remains unclear whether the striatum is directly involved in language processing or whether its role in decision-making has an indirect effect on language performance. We addressed this issue by using the drift diffusion model (DDM) (Ratcliff, 1978; Ratcliff & McKoon, 2008; Vandekerckhove & Tuerlinckx, 2008; Voss & Voss, 2007; Wagenmakers et al., 2007; Wiecki et al., 2013) to assess decision-making and core linguistic processing separately in HD mutation carriers. The DDM makes it possible to model the choice between two alternative responses and to evaluate decision-making and non-decision-making processes separately. We tested premanifest mutation carriers, HD patients and their matched controls in a simple decision-making task in which the participants were asked to distinguish between two sequences of stimuli. Two contrasting sets of stimuli were used, one in which the stimuli were linguistic in nature (syllables) and one in which the stimuli were non-linguistic (pure tones). We evaluated the decision and non-decision parameters of the DDM and their contributions to the performances of premanifest mutation carriers and HD patients in terms of response time and discriminability (sensitivity to difference). We hypothesized that the language deficits displayed by carriers of the HD mutation might be due to an underlying impairment of decision-making. If this were the case, then (1) this deficit would be expected to affect the decision-making component of the DDM but not the non-decision-making component, (2) the deficit should be observable in both the linguistic and non-linguistic tasks and (3) the variance in linguistic performance should be better explained by the decision-making component of the model than by the non-decision component. Finally, as striatal atrophy is the most reliable marker for the monitoring of early disease progression (Mason et al., 2018; Paulsen et al., 2008, 2014; Tabrizi et al., 2011, 2012, 2013), we hypothesized that appropriate markers of cognitive symptoms would be correlated with brain atrophy. We used a voxel-based morphometry analysis to determine whether the model parameters and behavioral performances reflected brain degeneration in carriers of the HD mutation.

## 2. Materials and methods

We report how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study.

### 2.1. Participants

We recruited 93 native French-speaking participants for this study, 48 of whom were carriers of the mutation responsible for Huntington's disease (abnormal CAG expansion of at least 36 repeats in the huntingtin gene (Walker, 2007). Participants were evaluated with the UHDRS (Huntington Study Group, 1996), the Mattis Dementia Rating Scale (MDRS) (Mattis, 1976), the forward digit span test and the categorical fluency test. The mutation carriers comprised 38 patients at an early stage of the disease (earlyHD; stages I and II of the classification based on UHDRS total functional capacity (TFC) score (Shoulson, 1981)) and 20 individuals at the premanifest stage (preHD; defined by a TFC of 13 and a Total Motor Score (TMS) < 5) (Tabrizi et al., 2009). We also recruited 45 healthy participants as controls. The sample size was estimated on the basis of previous work (Teichmann et al., 2009). The three groups (controls, preHDs, earlyHDs) were matched for demographic variables, such as sex [ $\chi^2(2, N = 93) = .37, p = .83$ ], handedness [ $\chi^2(4, N = 93) = 2.14, p = .71$ ], and years of education [ $F(2, 90) = .85, p = .43$ ]. The groups differed in age [ $F(2, 90) = 5.05, p < .01$ ]. The controls were matched with the preHDs ( $\beta = 4.03, p = .22$ ) and earlyHDs ( $\beta = 4.19, p = .13$ ) for age, but the preHDs were younger than the earlyHDs ( $\beta = 8.22, p < .01$ ), reflecting the natural course of the disease (Langbehn et al., 2004). None of the participants had any hearing problems or neurological or psychiatric disorders other than Huntington's disease in mutation carriers. The demographic and clinical features of the participants are summarized in Table 1 and Supplementary Table 1.

The study was performed in accordance with the Declaration of Helsinki (2008). Participants were recruited from an outpatient clinical biomarker study (NCT01412125) approved by the ethics committee of Henri Mondor Hospital (Créteil, France). The inclusion phase of the studied ended when 45 valid brain MRI scans had been obtained from mutation carriers. All participants gave written informed consent for participation. No part of the study procedures or analysis plans was pre-registered prior to the research being conducted.

**Table 1 – Demographic and neuropsychological data for participants.**

	Controls	preHDs	earlyHDs
Number of participants	45	20	28
Number of MRI scans	–	20	25
Sex	26 F/19 M	13 F/7 M	16 F/12 M
Handedness	38 R/7 L	19 R/1 L	25 R/3 L
Age in years <sup>a</sup>	45.4 ± 6.1	41.4 ± 10.3	49.6 ± 11.4
Education in years	13.4 ± 2.1	14.1 ± 2.4	13.1 ± 3.2
Number of CAG repeats	–	43 ± 2.5	45.3 ± 4.8
TFC	–	13 ± 0	11.7 ± 1
TMS	–	.6 ± 1.2	27.5 ± 11.2
Burden Score	–	297.1 ± 86.1	444.4 ± 110.2
MDRS	–	141.8 ± 2.8	132.9 ± 9.1

Number of CAG repeats: pathological threshold >35; Burden score = (CAG-35.5) x age; MDRS: pathological score <136/144; F: female, M: male; R: right, L: left; mean ± standard deviation are reported; °: cohort of controls restricted to 27 participants.

<sup>a</sup> EarlyHDs are different from preHDs ( $p < .01$ ).



## 2.2. Materials and procedure

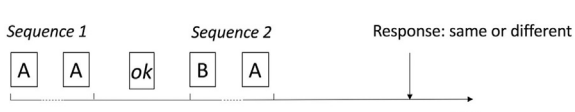
We evaluated each step, from perception to motor action, with a simple AX auditory discrimination task in which participants were asked to compare two sequences and to indicate whether they were the same or different by pressing P for “pareil” (the French word for “same”) or D for different, on an AZERTY keyboard (Fig. 1). Participants were informed that their accuracy and response time would be recorded. They were asked to answer as accurately and quickly as possible.

Using this simple task, we were able to collect sufficient data for drift diffusion model (DDM) analyses. This approach assumes that decision-making takes time due to the need to accumulate evidence. Decision-making is a noisy process in which sufficient evidence for a decision to be taken must be extracted from the stimulus, through the analysis of samples comprising multiple elements of evidence. DDM analyses were used to extract four parameters (see Fig. 2): (1) drift rate ( $v$ ), the rate of evidence accumulation, which is determined by the quality of the evidence signal extracted from the stimulus; (2) the decision boundary ( $a$ ), the threshold amount of evidence required for the participant to make a decision; (3) bias ( $zr$ ), corresponding to an *a priori* bias in favor of one of the alternatives and (4) the non-decision time parameter ( $Ter$ ), corresponding to the time required for non-decisional processes, such as stimulus processing, motor preparation and execution (Ratcliff et al., 2016). We then compared these parameters between mutation carriers and controls with two sets of stimuli (linguistic and non-linguistic stimuli) to identify the precise step impaired in the performance of this simple task.

The participants were asked to sit in front an Apple MacBook Pro, in a quiet room, wearing headphones tuned to ensure hearing comfort. To ensure the best possible comparison, we focused in the language task on a low-level language component, phonological processing, in a task optimised to induce performance differences between controls and HD mutation carriers. Phonological processing has three advantages: 1) it is automatic (Dehaene-Lambertz et al., 2000; Sun et al., 2015); 2) it has a distinct brain signature from non-phonological processing (Jacquemot et al., 2003); 3) it is sensitive to short-term memory load (Jacquemot et al., 2006; Jacquemot & Scott, 2006; Teichmann et al., 2009).

Sequences composed of pseudowords (CVC) were played through the headphones in the linguistic task.

For the non-linguistic task, sequences of pure tones were played through the headphones. The sequences were of variable length, comprising two to eight stimuli, in both sets of conditions. In each task, the first sequence was followed by 300 msec of silence, “OK” and then another 300 msec of silence



**Fig. 1 – The participants heard two sequences (sequence 1 and sequence 2) separated by “OK” and had to decide whether the two sequences were the same or different. In the example given here, the two sequences are different and the expected response is, therefore, “different”.**

before the second sequence was delivered, to prevent the use of a low-level echoic memory buffer (Jacquemot et al., 2006; Morton et al., 1981). The perceptual difference between stimuli within a sequence varied. In the linguistic task, half the stimuli were considered phonologically close (e.g., *jode/3od* and *jote/3ot*), whereas the other half were phonologically distant (e.g., *mibe/mib* and *choule/jul*). The stimuli in each sequence had a mean duration of 350 msec and were separated by 100 msec. In the non-linguistic task, stimuli were considered acoustically close at 841 and 1000 Hz (a quarter of an octave apart) and acoustically distant at 500 and 1000 Hz (one octave apart) (Zatorre & Belin, 2001). Stimuli are archived in a publicly accessible repository (<https://osf.io/47xz2/>). The mean duration of stimuli in non-linguistic sequences was 500 msec, and stimuli were separated by 100 msec. In “different” trials of the AX task (50% of the trials), the positions of the different stimuli within the sequence were balanced, to prevent anticipation. In each task (linguistic and non-linguistic), there were 10 trials per length and per distance, resulting in 140 trials in total. Trials were randomized within blocks of sequences of the same length. Blocks were ordered in ascending order of sequence length. Accuracy and response times were recorded after each trial. The participant's response in each trial triggered the presentation of the next trial, 600 msec later. The non-linguistic task was performed after a training session of six trials and was followed by the linguistic task.

## 2.3. Data analysis

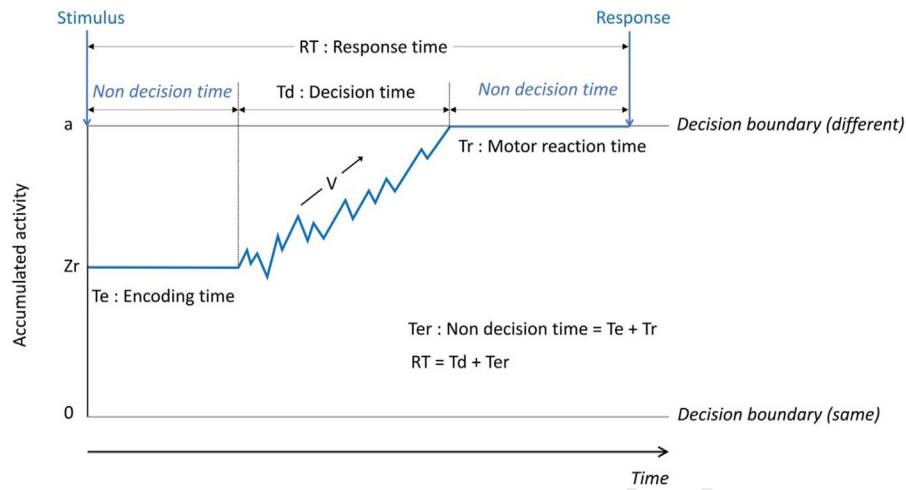
Analysis code is archived in a publicly accessible repository (<https://osf.io/47xz2/>).

### 2.3.1. Model-free analysis

We calculated discriminability by computing same-different  $d$ -prime scores for each participant. We used the following formula to calculate  $d$ -prime, in accordance with signal detection theory for classification designs for the same-different discrimination of independent observations: for  $pc \geq .5$ ,  $d' = 2z \{1/2[1 + [2pc - 1]1/2]\}$  and for  $pc < .5$ ,  $d' = 2z \{1/2[1 + [2(1 - pc) - 1]1/2]\}$ , where  $z$  is the  $z$ -transform, and  $pc$  is the proportion of correct responses (Macmillan & Creelman, 2005). If a value of infinity was obtained for  $d$ -prime, it was replaced by a value of plus or minus 6.58 (corresponding to perfection). Higher  $d$ -prime values indicate a better capacity of the participant to discriminate between two sequences, ruling out a possible bias in favor of a “same” or “different” response. A  $d$ -prime value of zero is equivalent to responding by chance, and a  $d$ -prime score of 6.58 corresponds to perfection.

We analyzed response times for the trials in which correct answers were given (data loss of 22%). We excluded all trials in which participants responded before the sequence had been completed, leading to a further loss of .04% of the data. Response times were normalized by logarithmic transformation before behavioral analyses (Baayen & Milin, 2010).

We used the “lme4 1.1–27.1” R package (Bates et al., 2015) to fit linear mixed-effect models, with participant as a random intercept. Item was also treated as a random intercept in the analysis of response times, as we used the full distribution. A type III ANOVA was performed by Satterthwaite's method to identify main effects. All post-hoc comparisons were



**Fig. 2 – Example trajectory of the drift diffusion model for a “different” trial in which the correct answer was given. Two decision boundaries (0 and a) correspond to the thresholds for the “same” and “different” decisions. The drift rate ( $v$ ) is the rate of evidence accumulation. The process of diffusion begins at  $z_r$  ( $= .5$  if there is no bias in favor of one of the alternatives) and continues until one of the two boundaries is reached. The response time (RT) is the sum of the time taken for the diffusion process ( $T_d$ , decision time) and the non-decision time ( $T_{er}$ ) required for stimulus processing ( $T_e$ ) and response output ( $T_r$ ),  $RT = T_e + T_d + T_r$ .**

corrected for multiple comparisons with a single-step method. All analyses were performed with R version 4.1.0.

### 2.3.2. DDM analysis

Hierarchical Bayesian DDM (HDDM) analysis was performed on trial-by-trial RTs (Kassubek et al., 2004b; Mason et al., 2018; Paulsen et al., 2008; Paulsen & Long, 2014; Tabrizi et al., 2011, 2012, 2013; Wiecki et al., 2013) and four parameters were extracted from the best-fitting model: (1) drift rate ( $v$ ), (2) the decision boundary ( $a$ ); (3) bias ( $z_r$ ), and (4) the non-decision time parameter ( $T_{er}$ ) (Ratcliff & McKoon, 2008) (see the details of the DDM analysis in the supplementary material). These parameters were compared between the various groups (controls, preHDs and earlyHDs) and tasks (linguistic and non-linguistic) by Bayesian methods, because the hierarchical structure of the model violates the assumption of independence underlying classical frequentist statistics. Bayesian probabilities are denoted  $P(\text{hypothesis})$  and express the probability of a hypothesis being true. For example, if we wanted to test the hypothesis that earlyHDs have a higher drift rate than controls ( $P(v_{\text{earlyHDs}} > v_{\text{controls}})$ ), then a probability of .95 would indicate that there was a 95% chance of the hypothesis being true, whereas a probability of .05% would indicate that there was a 95% chance of the converse (earlyHDs having a lower drift rate than controls ( $P(v_{\text{earlyHDs}} > v_{\text{controls}}) = 1 - P(v_{\text{earlyHDs}} < v_{\text{controls}})$ )) being true. A probability of .5 would indicate that both hypotheses (higher or lower drift rate) were equally likely. We performed two-tailed tests and therefore considered values of  $P > .975$  or  $< .025$  to be significant.

### 2.3.3. Contribution of HDDM parameters to the variance of performance in linguistic and non-linguistic tests

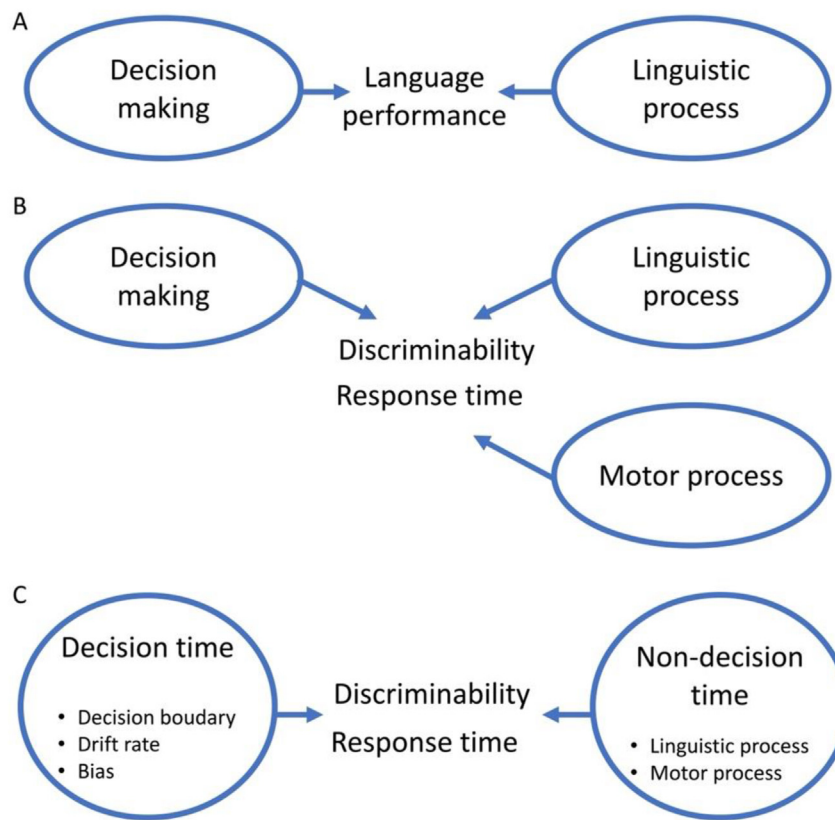
Finally, we evaluated the contribution of underlying cognitive deficits to deficits in discriminability and response time. To characterize these deficits, we centered each measure

(discriminability, response time, drift, decision boundary, bias and non-decision time) on the value of the control group to represent the deviation from a “normal” behavior. For each measure and each HD mutation carrier, the centered measure ( $\Delta$ ) was calculated by subtracting the mean of the control group. For example, a positive centered response time  $\Delta(\text{response time})$  therefore represents an elongation of response time compared to controls. We then evaluated the proportion of the variance of  $\Delta(\text{discriminability})$  and  $\Delta(\text{response time})$  explained by the various parameters:  $\Delta(\text{drift})$ ,  $\Delta(\text{decision boundary})$ ,  $\Delta(\text{bias})$ ,  $\Delta(\text{non-decision time})$  (Fig. 3). For each task (linguistic and non-linguistic) and each group of mutation carriers (preHDs and earlyHDs), we fitted a linear model with  $\Delta(\text{discriminability})$  or  $\Delta(\text{response time})$  as a dependent variable and the centered parameters as predictors. Each model accounted for a proportion of the variance ( $R^2$ ) of the dependent variable. We calculated the relative importance of the contribution of each predictor to the proportion of the variance explained, with the “relaimpo” package of R (Gromping, 2006). The order of the predictors in the linear model affects the proportion of the variance explained. We therefore used the recommended “lmg” metrics from Lindeman, Merenda and Gold (Lindeman et al., 1980) providing an average over all possible orderings.

## 2.4. MRI data collection and analyses

Three-dimensional T1-weighted structural MRI scans were acquired with an MP-RAGE sequence on a Siemens symphony 1.5 T whole-body scanner (Henri Mondor Hospital, Paris, France) with a 12-channel head coil (TR = 2400 msec, TE = 3.72 msec, TI = 1000 msec, FA = 8°, FOV = 256\*256 mm<sup>2</sup>, 1-mm isotropic voxel, slice thickness = 1 mm, no inter-slice gap, 160 sagittal sections).

In total, 45 brain MRI scans were obtained from mutation carriers (20 preHDs and 25 earlyHDs) within about three months



**Fig. 3 – Factors affecting language performance. A. Language performance results from both the core linguistic process and decision-making. B. In this study, language performance was assessed with a discrimination task. The response required the participant to press a computer key, an action that involves a motor response. Performance was assessed by determining discriminability and response time. C. Drift diffusion models can be used to analyze discrimination task results, assuming that the decision between two alternative responses requires an accumulation of evidence in favor of one or other of the alternatives. Language performance can be broken down into decision time and non-decision time (corresponding to core linguistic and motor processes).**

of testing in the auditory discrimination tasks. These scans were compared with 31 scans from external healthy participants (imaging controls), matched with the mutation carriers for age and sex ( $46.1 \pm 13.9$  years old, 14 women and 17 men).

Structural MRI data were preprocessed with Statistical Parametric Mapping software (SPM12 v.6906) (<http://www.fil.ion.ucl.ac.uk/spm/>) and its Computational Anatomy Toolbox (CAT12 r1200) (<http://www.neuro.uni-jena.de/cat/>) in MATLAB R2014a. For each participant, the image was manually centered on the anterior commissure and realigned. In accordance with CAT12 manual recommendations, each image was corrected for intensity bias, registered to MNI space by applying a high-dimensional DARTEL approach (Ashburner, 2007), tissue-classified and modulated to reflect tissue volumes before spatial normalization. Sample homogeneity was checked, and all images were retained. Finally, the gray matter segment for each participant was smoothed with a 6 mm FWHM Gaussian kernel.

We first performed a voxel-by-voxel one-way two-sample t-test on the entire brain, to assess gray matter volume loss in mutation carriers relative to healthy participants. Results were corrected for multiple comparisons by family-wise error

correction (FWE) ( $p\text{-FWE} < .05$ ). Only clusters of more than 200 voxels were retained and used to generate a binary mask with the MarsBaR region-of-interest toolbox (R0.44) (<http://marsbar.sourceforge.net/>) for SPM12.

We then explored the relationships between gray matter volume in the previously identified region of gray matter atrophy and our measurements of interest (mean discriminability, mean response time, decision boundary, drift rate of evidence accumulation, relative bias, and non-decision time) for each task (linguistic and non-linguistic) independently. We also investigated the relationship between gray matter volume and classical neuropsychological measurements and tests, such as the TMS, disease burden score (Penney et al., 1997), symbol digit modalities test (SDMT), forward span test, Stroop interference and 2 min categorical fluency test (Wechsler, 1958). Given that the region of interest did not comply with the assumptions behind FWE correction (Penny et al., 2011; Worsley et al., 1996), we applied a Bonferroni correction ( $p\text{-BONF} < .05$ ). In all analyses, total intracranial volume was used as a covariate to correct for differences in brain size, as recommended in the CAT12 voxel-based morphometry manual.



## 2.5. Data availability

All participants signed an informed consent form guaranteeing data confidentiality. The conditions of our ethics approval, including the ethical consent by participants, do not permit public archiving of anonymized study data. Readers seeking access to the data should contact Prof. Anne-Catherine Bachoud-Lévi. Access will be granted to named individuals in accordance with ethical procedures governing the reuse of sensitive data, including a research partnership and the completion of a data transfer agreement provided by the APHP. Legal copyright restrictions prevent public archiving of the UHDRS, which can be obtained from UHDRS® | - Huntington Study Group.

## 3. Results

### 3.5.1. Model-free analysis

Three participants (one patient with early manifest disease and two healthy participants) did not perform the linguistic task due to fatigue and were excluded from the analysis. This did not affect group matching.

The mean discriminability ( $d$ -prime) value is presented as a function of the mean response time in Fig. 4 for the linguistic (A) and non-linguistic (B) tasks.

For discriminability,  $d$ -prime revealed a main effect of group ( $F(2, 93) = 21.9, p < .001$ ) and task ( $F(1, 90) = 41.0, p < .001$ ), with participants having a higher  $d$ -prime in the non-linguistic task than in the linguistic task ( $\beta = .28 \pm .04, 95\% \text{ CI} = [.18, .39], z = 6.41, p < .001$ ). EarlyHDs were less sensitive (lower  $d$ -prime) than controls ( $\beta = .81 \pm .13, 95\% \text{ CI} = [-1.13, -.49], z = 6.15, p < .001$ ) and preHDs ( $\beta = .88 \pm .17, 95\% \text{ CI} = [-1.27, -.48], z = 5.35, p < .001$ ). There was no interaction with or main effect of age.

For response time, there was a main effect of group ( $F(2, 93) = 32.9, p < .001$ ) and task ( $F(1, 56) = 9.6, p < .01$ ) and an interaction between group and task ( $F(2, 19,939) = 7.5, p < .001$ ). EarlyHDs reacted more slowly than controls ( $\beta = .76 \pm .10, 95\% \text{ CI} = [.51, 1.01], z = 7.81, p < .001$ ) and preHDs ( $\beta = .73 \pm .12, 95\% \text{ CI} = [.42, 1.05], z = 6.03, p < .001$ ). Response times were slower in the linguistic task for preHDs ( $\beta = .16 \pm .06, 95\% \text{ CI} = [-.02, -.31], z = 3.01, p < .05$ ) and controls ( $\beta = .20 \pm .05, 95\% \text{ CI} = [.07, .34], z = 3.80, p < .001$ ), but not for earlyHDs ( $\beta = .12 \pm .05, 95\% \text{ CI} = [-.02, .26], z = 2.24, p = .12$ ).

Thus, earlyHDs performed less well than the other groups and had a longer RT in both the linguistic and non-linguistic tasks, whereas the performance of preHDs was not significantly different from that of controls.

### 3.6. DDM analysis

The probability distributions (posterior estimates) of the decision boundary, drift rate, relative bias and non-decision time for each group and task are shown in Fig. 5.

EarlyHDs had a higher decision boundary and a lower drift rate than controls and preHDs in both the linguistic and non-linguistic tasks. They, therefore, needed to accumulate more evidence to discriminate between “same” and “different”

stimuli, and they accumulated this evidence more slowly (all Bayesian probabilities  $P = 1$ ). No differences were found between preHDs and controls for decision threshold ( $P(a_{\text{preHDs/linguistic}} < a_{\text{controls/linguistic}}) = .71, P(a_{\text{preHDs/non-linguistic}} < a_{\text{controls/non-linguistic}}) = .66$ ) or drift rate, ( $P(v_{\text{preHDs/linguistic}} > v_{\text{controls/linguistic}}) = .82, P(v_{\text{preHDs/non-linguistic}} > v_{\text{controls/non-linguistic}}) = .66$ ).

Non-decision time was longer for preHDs and earlyHDs than for controls in the linguistic task ( $P(\text{Ter}_{\text{preHDs/linguistic}} > \text{Ter}_{\text{controls/linguistic}}) > .99, P(\text{Ter}_{\text{earlyHDs/linguistic}} > \text{Ter}_{\text{controls/linguistic}}) > .99$ ), whereas it did not differ significantly between groups in the non-linguistic task ( $P(\text{Ter}_{\text{preHDs/non-linguistic}} > \text{Ter}_{\text{controls/non-linguistic}}) = .04, P(\text{Ter}_{\text{earlyHDs/non-linguistic}} > \text{Ter}_{\text{controls/non-linguistic}}) = .60, P(\text{Ter}_{\text{preHDs/non-linguistic}} > \text{Ter}_{\text{earlyHDs/non-linguistic}}) = .95$ ).

EarlyHDs displayed a bias in favor of the “same” response in both linguistic ( $P(z_{\text{earlyHDs/linguistic}} > .5) = 1.00$ ) and non-linguistic tasks ( $P(z_{\text{earlyHDs/non-linguistic}} > .5) = .97$ ). No such bias was observed in preHDs and controls ( $P(z_{\text{preHDs/linguistic}} > .5) = .39, P(z_{\text{preHDs/non-linguistic}} > .5) = .21, P(z_{\text{controls/linguistic}} > .5) = .84, P(z_{\text{controls/non-linguistic}} > .5) = .21$ ). EarlyHDs displayed a higher degree of bias than either controls or preHDs in both tasks (one-tailed tests, all  $P > .95$ ). By contrast, there was no significant difference in bias between preHDs and controls ( $P(z_{\text{controls/linguistic}} > z_{\text{preHDs/linguistic}}) = .78, P(z_{\text{controls/non-linguistic}} > z_{\text{preHDs/non-linguistic}}) = .59$ ).

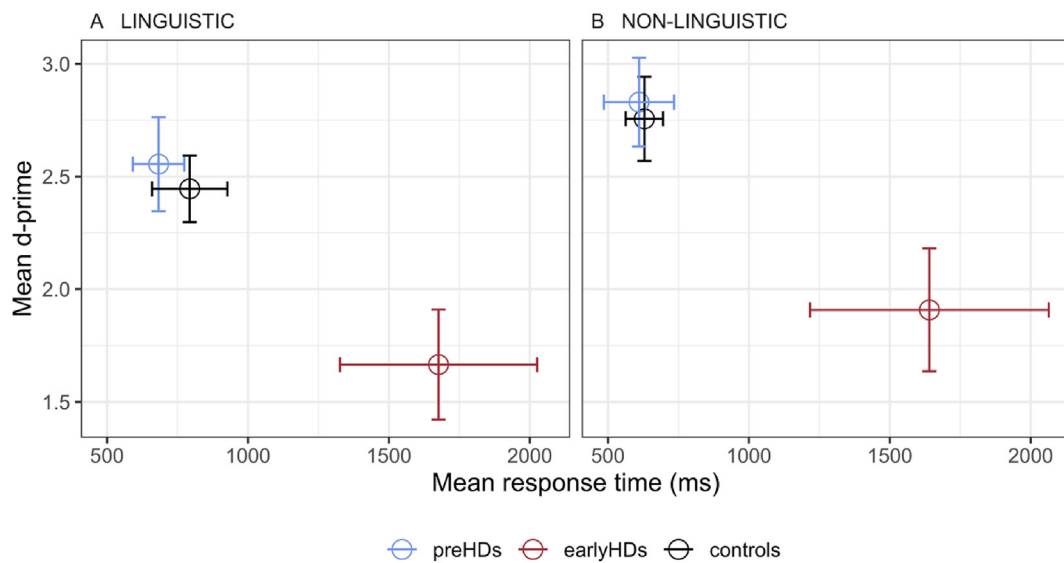
These results indicate that earlyHDs need to accumulate more evidence than controls and preHDs to take a decision. They also accumulated evidence more slowly than the controls and displayed a bias in favor of “same” responses, in both linguistic and non-linguistic tasks. Conversely, non-decision time was longer in preHDs and earlyHDs than in controls in the linguistic task, but not in non-linguistic tasks.

### 3.7. Contribution of HDDM parameters to the variance of linguistic and non-linguistic task performances

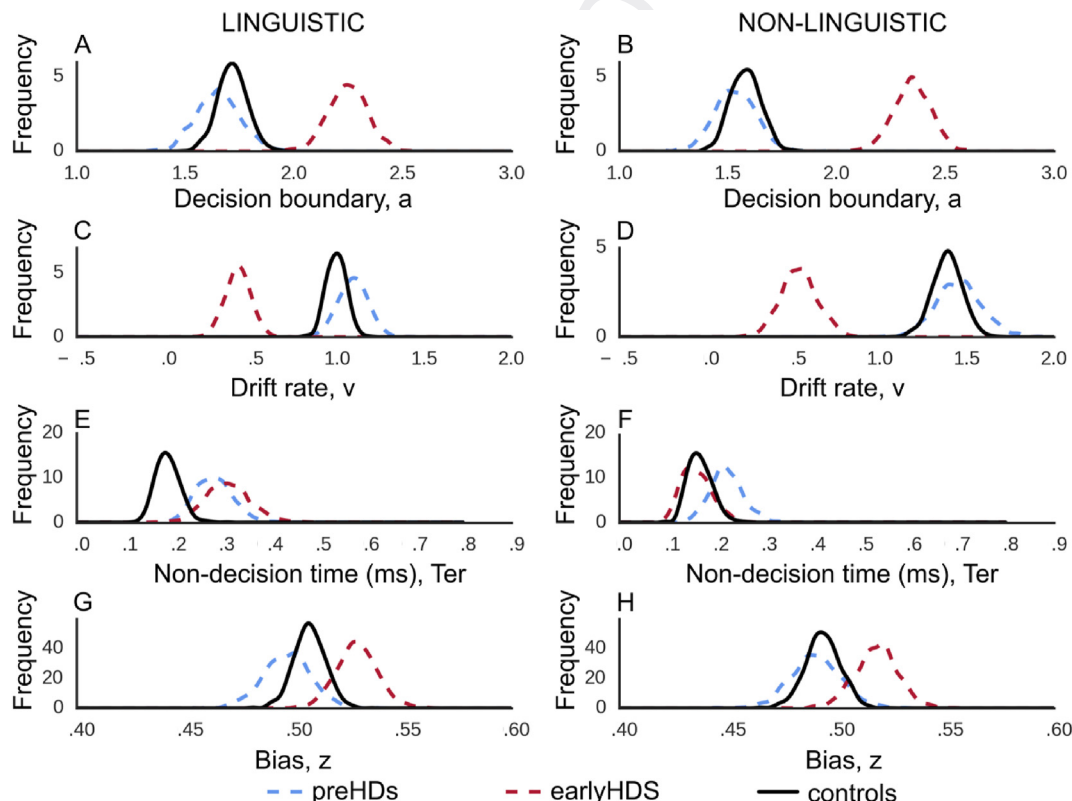
We assessed the contributions of the decision and non-decision deficits highlighted by HDDM analysis to the deficits in performance in Table 2. In this analysis, significance for a particular model implies that deviation from controls in parameters of the HDDM explain a significant proportion of the observed deviation from controls in response time and discriminability ( $d$ -prime). The significant models explained between 84% and 98% of the variance for discriminability and 57%–96% of the variance for response time.

The results for preHDs and earlyHDs were similar (see Fig. 6). In the linguistic task, a large proportion of the variance of  $\Delta(\text{response time})$  and  $\Delta(\text{discriminability})$  was explained by deviation from controls in decision parameters (from 74% to 98%), with a much smaller proportion (from less than 1%–20%) explained by deviation from controls in non-decision parameters. In the non-linguistic task, a large proportion of the variance of response time and discriminability was also explained by decision parameters (48%–94%), with a much smaller proportion explained by non-decision parameters (from less than 1%–14%).

These results show that deviation from controls in decision time parameters make a much larger contribution than the deviation from controls in non-decision time parameters to the variance of the deviation from controls for both response



**Fig. 4 – Model-free results. Mean discriminability (d-prime) as a function of mean response time for the linguistic task (A) and the non-linguistic task (B). Points represent the mean values, and lines, the range plus or minus two standard errors of the mean. EarlyHDs are shown in red, preHDs are shown in blue and controls are shown in black.**



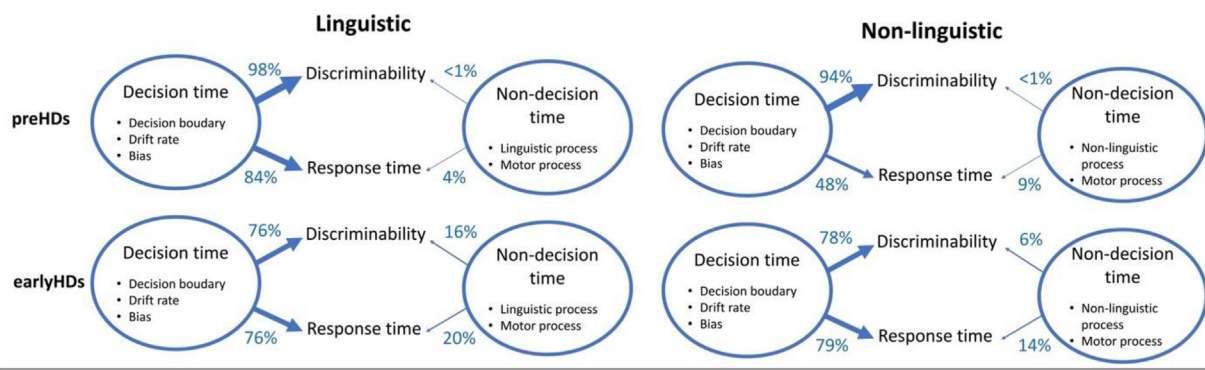
**Fig. 5 – Posterior probability distributions of HDDM parameters for each group and set of conditions. Data are shown for the linguistic (left) and non-linguistic (right) tasks. Dashed lines represent the groups of individuals carrying the mutation, blue for preHDs and red for earlyHDs. The data for controls are shown as solid black lines.**

time and discriminability in participants carrying the HD mutation (preHDs and earlyHDs), regardless of whether the task performed is linguistic or non-linguistic in nature. In the linguistic task test conditions,  $\Delta(\text{non-decision time})$  accounted for no more than 4% of the variance of the language

performance of preHDs and no more than 20% of the variance of language performance for earlyHDs. Non-decision time includes both linguistic (stimulus perception, stimulus decoding to extract decision-related information, memory access) and motor processes. We investigated the relative

**Table 2 – Contributions of the deficits highlighted by DDM model parameters to discriminability and response time performance. For each task (linguistic or non-linguistic), each group (preHDs or earlyHDS), and each “deficit” in response time ( $\Delta$ (Response time)) or discriminability ( $\Delta$ (discriminability)), the F-statistic of the model is reported, together with the proportion of the total variance explained. For each task (linguistic or non-linguistic), each group (preHDs or earlyHDS), and each “deficit” in response time ( $\Delta$ (Response time)) or discriminability ( $\Delta$ (discriminability)), we then report the coefficient  $\pm$  standard error and the proportion of the variance explained by each predictor:  $\Delta$ (Decision boundary),  $\Delta$ (Drift rate),  $\Delta$ (Non-decision time),  $\Delta$ (Relative bias) included in the model. ns: non-significant,  $< .1$ ,  $**$ :  $< .01$ ,  $***$ :  $.001$ . preHDs: premanifest participants, earlyHDS: patients at early stages of HD.**

		Linguistic			Non-linguistic		
		Coeff $\pm$ SD	p	Explained variance (%)	Coeff $\pm$ SD	p	Explained variance (%)
preHDs	<b><math>\Delta</math>(discriminability)</b>						
	Model	F(4,14) = 184.4	***	98%	F(4,15) = 58.3	***	94%
	$\Delta$ (Decision boundary)	.75 $\pm$ .07	***	13%	.39 $\pm$ .06	***	11%
	$\Delta$ (Drift rate)	1.09 $\pm$ .04	***	84%	1.09 $\pm$ .08	***	80%
	$\Delta$ (Non-decision time)	-.04 $\pm$ .04	ns	<1%	-.04 $\pm$ .06	ns	<1%
	$\Delta$ (Relative bias)	-.001 $\pm$ .04	ns	1%	.05 $\pm$ .07	ns	3%
	<b><math>\Delta</math>(Response time)</b>						
	Model	F(4,14) = 25.1	***	88%	F(4,15) = 5.1	**	57%
	$\Delta$ (Decision boundary)	.55 $\pm$ .10	***	53%	.73 $\pm$ .35	.	27%
	$\Delta$ (Drift rate)	-.10 $\pm$ .06	.	28%	-.62 $\pm$ .44	ns	18%
$\Delta$ (Non-decision time)	.14 $\pm$ .06	*	4%	.70 $\pm$ .37	.	9%	
$\Delta$ (Relative bias)	.01 $\pm$ .05	ns	3%	.17 $\pm$ .41	ns	3%	
earlyHDS	<b><math>\Delta</math>(discriminability)</b>						
	Model	F(4,22) = 63.5	***	92%	F(4,23) = 30.1	***	84%
	$\Delta$ (Decision boundary)	.24 $\pm$ .07	**	7%	.17 $\pm$ .06	*	5%
	$\Delta$ (Drift rate)	1.42 $\pm$ .13	***	61%	1.66 $\pm$ .18	***	69%
	$\Delta$ (Non-decision time)	-.06 $\pm$ .02	*	16%	-.05 $\pm$ .03	ns	6%
	$\Delta$ (Relative bias)	-.07 $\pm$ .08	ns	8%	-.02 $\pm$ .10	ns	4%
	<b><math>\Delta</math>(Response time)</b>						
	Model	F(4,22) = 119.4	***	96%	F(4,23) = 69.1	***	92%
	$\Delta$ (Decision boundary)	1.10 $\pm$ .08	***	57%	2.15 $\pm$ .18	***	66%
	$\Delta$ (Drift rate)	-.07 $\pm$ .16	ns	18%	-.29 $\pm$ .50	ns	12%
$\Delta$ (Non-decision time)	.17 $\pm$ .02	***	20%	.35 $\pm$ .10	***	14%	
$\Delta$ (Relative bias)	.01 $\pm$ .10	ns	1%	-.29 $\pm$ .29	ns	<1%	



**Fig. 6 – Contribution of decision-time and non-decision time parameters, expressed as a percentage, to the performance of preHDs and earlyHDS in terms of discriminability (d-prime) and response time, in the linguistic and non-linguistic tasks. preHD: premanifest participants, earlyHDS: patients at early stages of HD.**

contributions of linguistic and motor processes to non-decision time in HD mutation carriers, by determining whether a motor score (UHDRS motor score) or a language score (UHDRS categorical fluency) better explained the non-decision time, depending on the task (linguistic or non-linguistic). We found an interaction between UHDRS motor

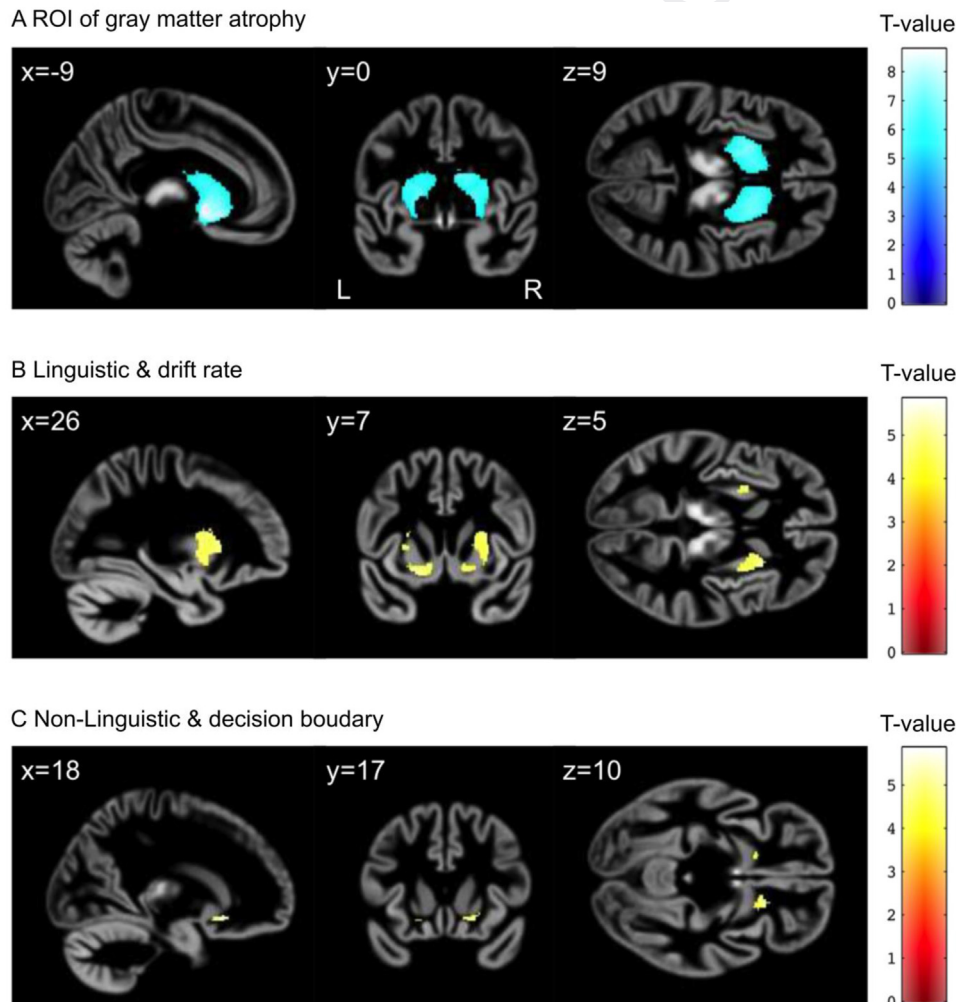
score and the task ( $F(1, 83) = 10.9, p < .01$ ), with post-hoc models showing that UHDRS motor score could explain non-decision time only in the linguistic task ( $F(1, 40) = 23.1, p < .001$ , vs  $F(1, 42) = 1.9, p = .17$  for the non-linguistic task). By contrast, there was no interaction between categorical fluency score and task ( $F(1, 83) = .05, p = .82$ ), and no effect of

categorical fluency score in any of the tasks (all  $p$ -values  $>.05$ ). This suggests that the non-decision time in the linguistic task is better explained by a motor component than by a linguistic component.

### 3.8. Relationship between brain structure and HDDM parameters

Mutation carriers displayed clustered decreases in gray matter volume in the striatum (right and left caudate nucleus, putamen, globus pallidus and ventral striatum) relative to controls (9495 voxels, cluster-level  $p$ -FEW  $<.05$ ) (Fig. 7A). The clustered decreases in volume observed defined the region of atrophy in mutation carriers, which was investigated in more detail in subsequent analyses.

Model-free measurements (mean discriminability and mean response time) were not correlated with gray matter volume in the region of striatal atrophy in mutation carriers, in any of the tasks (peak-level  $p$ -BONF  $>.05$ ). By contrast, HDDM parameters were correlated with gray matter volume. In the linguistic task, the drift rate for evidence accumulation was positively correlated with gray matter volume in the ventral striatum and putamen in mutation carriers (Fig. 7B and Table 3). In the non-linguistic task, the decision boundary was inversely correlated with gray matter volume in the ventral striatum in mutation carriers (Fig. 7C and Table 3). No other significant correlations were found with any of the other parameters (peak-level  $p$ -BONF  $>.05$ ). The correlation between neuropsychological measurements and gray matter volume atrophy is reported in Supplementary Table 2.



**Fig. 7 – Voxel-based morphometry analyses. (A)** Statistical map of areas displaying a significant decrease in gray matter volume in Huntington's mutation carriers relative to healthy controls ( $p$ -FWE  $<.05$ ), defining our region of interest. **(B)** Statistical map of positive regression between gray matter and drift rate in the region of interest **(C)** Statistical map of negative regression between gray matter and the decision boundary in the region of interest. For **(B)** and **(C)**, results were subjected to Bonferroni correction according to the number of voxels in the region of interest ( $p$ -BONF  $<.05$ ). Statistical maps were thresholded at  $p < 2.8e-5$  for the purposes of illustration. The results are displayed on a gray matter template for our cohort obtained with the TOM8 toolbox (<http://www.neuro.uni-jena.de/software/tom/>) for SPM.



**Table 3 – Voxel-based morphometry analyses. Significant correlations between gray matter volume and model-free and model-based measurements for Huntington's mutation carriers. The analyses were restricted to a region of interest of 9495 voxels in which Huntington's mutation carriers displayed gray matter atrophy relative to controls ( $p$ -FEW  $<.05$ ). Results were subjected to Bonferroni correction for multiple testing. No voxel threshold was applied. R = right and L = left.**

Task	Parameter	Regression	Brain region	Side	Number of voxels	T	MNI coordinates		
							(x	y	z)
Linguistic	Drift rate	Positive	Ventral striatum	R	18	5.82	18	21	-10
				L	41	5.44	-15	10	-12
			Putamen	R	11	5.25	26	18	6
				L	4	5.16	30	2	12
				L	3	5.09	-28	4	12
Non-linguistic	Decision boundary	Negative	Ventral striatum	R	13	5.84	20	18	-12
				L	2	5.08	-15	12	-12

#### 4. Discussion

In this study, we addressed the issue of the role of the striatum in language and explored whether this structure is directly involved in language processing or whether its role in decision-making has an indirect effect on language performance. We compared performance between individuals with pre-manifest HD, patients at early stages of HD and controls, in an auditory discrimination AX task with two contrasting tasks: a linguistic and a non-linguistic task. Response times and discriminability scores differed between earlyHDs and controls but not between preHDs and controls. By contrast, HDDM analyses (Anders et al., 2017; Zhang et al., 2016), which assess the decision and non-decision components (including linguistic process) separately, showed that preHDs and earlyHDs have slower non-decision processes than controls in the linguistic task. In addition, earlyHDs were found to have impaired decision parameters, in both the linguistic and non-linguistic tasks, with slower rates of evidence accumulation (lower drift rate) and a higher decision boundary, indicating that they also required more evidence to come to a decision. As previously reported, a bias towards “same” responses was observed in earlyHDs (Teichmann et al., 2009). An analysis of the relative contributions of decision and non-decision parameters to the difference in discriminability and response time between HD mutation carriers (preHDs and earlyHDs) and controls showed that this difference was driven mostly by the decision component, regardless of the task (Fig. 6). In both tasks, only HDDM decision-time parameters were correlated with gray matter volume within the region of striatal atrophy in mutation carriers (Fig. 7, Table 3). Overall, our results suggest that impaired decision-making is more likely than a core linguistic deficit to be the underlying cause of language deficits in HD mutation carriers.

Our results show that the poor response times and discriminability of earlyHDs in the linguistic task were largely due to a slowing and impairment of the decision-making component of the task. Longer response times have frequently been reported in HD patients (García Ruiz et al., 2002; Tabrizi et al., 2009). They are generally attributed to a motor deficit (Teichmann et al., 2006; 2008a), but our findings indicate that this assumption is incorrect. We showed that this slowing was due to a decision component rather than a motor component (motor components being part of the

non-decision component). Indeed, the variance of response time was largely explained by slowness in decision-making rather than non-decision slowness (Fig. 6). An additive effect of motor slowness may be present, but its effect on response time is small. Nevertheless, the results obtained may be affected by disease stage considered, as the early stages are less marked by motor impairment.

Decision parameters were correlated with gray matter volume in the ventral striatum and putamen in the linguistic task, and with ventral striatum in the non-linguistic task (Fig. 7B and C and, 4C and Table 3). No such correlation was observed for non-decision parameters. Consistent with previous fMRI and EEG studies revealing a correlation between striatal activation and HDDM parameters in perceptual decision-making tasks (Frank et al., 2015; Mulder et al., 2014; Pisauro et al., 2017), our results suggest that the striatal atrophy has an impact on the decision boundary and drift rate, in turn affecting discriminability and response time (Forstmann et al., 2010). Gray matter loss in the striatum is one of the best markers of decline in HD (Kassubek et al., 2004b; Mason et al., 2018; Paulsen et al., 2014; Tabrizi et al., 2011, 2012, 2013) (Fig. 7, A). The striatum has been reported to gate inputs to the frontal cortex (Frank et al., 2001) as part of the general selection process in goal-directed performance (Giavazzi, Daland, Palminteri, Peperkamp, Brugières, et al., 2018; Grahm et al., 2009; Hart et al., 2014; Montague & Berns, 2002; Redgrave et al., 1999; Robbe & Dudman, 2020). Our results suggest that the striatal atrophy in both groups of mutation carriers (premanifest and early HD) affects the gating process, thereby affecting ability to select the most appropriate alternative from a list of competitive possibilities—motor, cognitive or linguistic—and to inhibit the other choices. Structures with the striatum play different roles in linguistic selection, with the putamen implicated in the selection of articulatory (Abutalebi et al., 2009, 2013; Gil Robles et al., 2005; Hervais-Adelman et al., 2011, 2015a, 2015b) and the caudate nucleus involved in the selection of more abstract linguistic alternatives at the morphological, syntactic, and lexicosemantic levels (Crinion et al., 2006; Giavazzi, Daland, Palminteri, Peperkamp, Brugières, et al., 2018; Jacquemot & Bachoud-Lévi, 2021b; Mestres-Missé et al., 2012; Teichmann, Gaura, et al., 2008, 2009, 2015; Tettamanti et al., 2005). In the linguistic task, the comparison of sequences of auditory stimuli may have required an auditory-articulatory loop (Hickok & Poeppel, 2004; Jacquemot et al., 2003), accounting for the correlation with putamen gray matter volume exclusively for linguistic stimuli.

The absence of a correlation between striatal atrophy and the non-decision component provides additional evidence for a role of the striatum in decision-making processes affecting language rather than in core linguistic processes. These executive processes take place in the fronto-striatal network regulating cognitive processing independently of the cognitive domain (Bogacz et al., 2010; Hertrich et al., 2020; Thibault et al., 2021). The deregulation of the selection process (lower drift rate and higher decision boundary) may account for impairment in any language task requiring selection from a group of alternatives: syntactic parsing requiring the selection of a single syntactic tree from a set of trees (Dominey & Inui, 2009; Friederici & Kotz, 2003b), verbal inflection morphology involves the selection of a morphological suffix (Longworth, 2005; Teichmann et al., 2005; Ullman et al., 1997) and the correct inflection of nouns and adjectives is required in tests of selection from several competing morphological alternatives (Nemeth et al., 2012; Giavazzi et al., 2018). Nevertheless, we cannot rule out the possibility that some parts of this selection process relate to a specific domain, rather than being general, as recently suggested by the case of a patient with an executive disorder affecting only language (Jacquemot & Bachoud-Lévi, 2021b). Within this fronto-striatal network, certain decision processes may therefore be involved specifically in language, but not strictly in core linguistic processes, as part of the language network (Ben Shalom & Poeppel, 2008; Hagoort, 2013; Jacquemot & Bachoud-Lévi, 2021b). The data presented here confirm the involvement of the striatum in the linguistic domain, via an executive process (see Jacquemot & Bachoud-Lévi, 2021a for a review).

By contrast to model-free behavioral results (discriminability and response time), which showed no difference between preHDs and controls, HDDM analysis revealed similar patterns for non-decision time parameters in all carriers of the HD mutation (whether premanifest or with early HD), different from that observed in the controls, with a longer non-decision time in the linguistic task for mutation carriers (Fig. 5). These longer non-decision times may result from either linguistic or motor deficits. A motor contribution to the deficit would be expected to result in longer non-decision times in both tasks. However, the non-decision time was longer only for the linguistic task, suggesting that slower linguistic processing was responsible, potentially due to an isolated core linguistic deficit in the two groups of mutation carriers. However, the stimuli lasted slightly longer in the non-linguistic task, giving the participants more time to prepare their motor responses than in the linguistic task. This could also potentially explain the longer non-decision times in the linguistic task than in the non-linguistic task. This hypothesis is supported by the correlation between UHDRS motor score and non-decision time, with this motor score better explaining non-decision time in the linguistic task than in non-linguistic task. This difference, which was detected in HDDM analysis, was not detectable in discriminability score or response time analyses, presumably because the non-decision time parameters accounted for less than 4% of the variance for linguistic performance in premanifest mutation carriers.

The HDDM approach and the tasks used here proved useful for assessing decision and language processes separately. Rather than analyzing response times exclusively in trials in

which the correct answer is given, as in analyses of response times and discriminability scores, HDDM combines the distributions of all responses and response times, and is therefore particularly sensitive to decline in HD (Bachoud-Lévi et al., 2001; Ho et al., 2003; Snowden et al., 2001). This method can handle a small number of observations (Ratcliff & Childers, 2015), and is appropriate for analyses of patient data in which there may be a higher proportion of incorrect responses. Our results, using phonological processing as a proof of concept, suggest that a decision-making deficit may account for the poor language performance of HD patients. However, as the linguistic system also includes morphological, lexical, syntactic components, etc., our results will benefit from a replication for other linguistic components to ensure their generalizability.

Finally, recent papers postulate that fronto-striatal atrophy may preferentially disrupt linguistic components that are related to motor or movement patterns: lexical-semantic mapping of movement (such as action verbs), integration of verbal and motor information (motor-verbal coupling), and syntax where sequencing and movement between units are involved (see Birba et al., 2017 for a review). In this embodiment theoretical framework, the motor component (part of the non-decision time parameter) of a linguistic task related to motor or movement patterns should much more contribute to the variance in response time and discriminability in the linguistic task than in the non-linguistic task. This could possibly be assessed by testing another component of language than phonology, which unlike phonology would rely on movement/motor information, such as a lexical task involving action verbs and nouns.

Our findings suggest that the striatum is involved in language through the modulation of decision-making. Indeed, we show here that the poor language performance of patients with striatal atrophy is better explained by a decision-making deficit than by a core linguistic process deficit. Further investigations are required to determine whether decision-making in the language domain is specific to language or involves a process common to the cognitive and motor domains.

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## Open practices

The study in this article earned Open Material badge for transparent practices. The materials for the study are available at: <https://osf.io/47xz2/>.

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## Uncited references

Fischl et al., 2002, Mason et al., 2018.

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## Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cortex.2023.04.016>.

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