Abstract

Objective: This study investigated whether dual tasks make disproportionately high demands in HD compared with controls, and also tested the Multiple Resources Theory. ***Method:*** Thirteen HD participants and 13 controls completed two dual task sets that varied in difficulty and complexity: set one paired simple choice reaction time (RT) with digit forward, and set two paired complex choice RT with digit backward. ***Results:*** We found that HD participants were overall slower; however, although they maintained similar levels of accuracy in the simple choice RT tasks with controls, their accuracy decreased in the complex choice RT tasks. In addition, we found that HD participants were more susceptible to speed-accuracy trade-offs. Despite that, they did not show greater dual task costs than controls. ***Conclusions:*** Overall, our findings do not support the Multiple Resources Theory, but they do provide some support for the Unitary Resource Theory and the attentional impairment hypothesis.

Keywords: choice reaction time, digit tasks, dual task costs, Huntington's disease, Multiple Resources Theory

Dual tasking refers to the performance of two tasks concurrently. From an ecological point of view, performance of multiple tasks concurrently is important for independent functioning, as it makes it possible to execute everyday tasks, such as cooking while talking. The limited dual task research in Huntington's disease (HD), and anecdotal reports of HD patients and their families, suggest that dual tasking is impaired in HD. Explanations for this impairment have been suggested, including deficits in resource allocation (Georgiou, Bradshaw, Phillips, & Chiu, 1996), attentional set-shifting (Lawrence et al., 1998), and lack of automaticity (Thompson et al., 2010). Although these explanations are plausible, the definitive basis of dual task impairments in HD is still unclear.

The progression of HD is generally slow, with the striatum the main site of early pathology (Georgiou-Karistianis et al., 2014; Jernigan & Butters, 1989). Cortical regions are also affected early (Aylward et al., 1998; 2011), and are likely to contribute to physical, emotional and cognitive symptoms (Deckel, Weiner, Szigeti, Clark, & Vento, 2000; Fenney, Jog, & Duval, 2008; Rosas et al., 2003). Of particular interest to this study is how HD participants perform dual tasks, which is often a source of complaint from both patients and family members. Not only do these clinical complaints establish the relevance of dual processing research in HD, the striatum's information processing architecture also implicates these structures as a potential neural substrate for dual processing. More specifically, the striatum processes inputs from divergent regions of the cortex through partially segregated parallel pathways, providing the basis for processing of multiple input/output pathways such as dual tasks (Alexander, DeLong, & Strick, 1986).

Dual tasking is usually studied using dual task paradigms. A number of theoretical frameworks have also been developed to explain dual task interference, including the

Multiple Resources Theory. The Multiple Resources Theory (Wickens & McCarley, 2008) postulates that attention has *multiple separate resource pools* (e.g., a visual resource pool, an auditory resource pool), each of which can be divided among concurrent tasks. According to this theory, information processing depends on four dichotomous dimensions: (1) processing stages, including perception-cognition and response, (2) perceptual modalities, including visual and auditory, (3) visual channels, including ambient and focal, and (4) processing codes, including spatial and verbal. When two tasks share common resources on these four dichotomous dimensions, divided attention deteriorates and dual task performance is less efficient (Wickens, 2002; Wickens & McCarley, 2008). Therefore, cross-dimensional tasks (e.g., visual-auditory) should lead to better processing than uni-dimensional tasks (e.g., visual-visual).

Another theory that attempts to explain dual task interference is the Unitary Resource Theory. This theory postulates that attention is a *single, limited capacity resource* that can be allocated to a single task or divided between different tasks, and which can be affected by task difficulty, among other things including individual's arousal levels and motivation (Kahneman, 1973). The Unitary Resource Theory posits that dual task performance deteriorates if one task is difficult and requires a large proportion of this limited attentional resource, because there is little left to support the performance of the other task. In case, where the demand exceeds the amount of attentional capacity, allocation strategies are used to establish on which tasks the attention resource should be allocated.

Empirical evidence on dual tasking in HD is sparse. For example, Sprengelmeyer et al. (1995) and Müller et al. (2002) used the same visual-auditory dual task paradigm that required participants to press a button to specific stimuli and a different button to discriminative stimuli. Therefore, although the input of the tasks was cross-dimensional (i.e., visual-auditory), the output was uni-dimensional (i.e., motor-motor). For one task of the dual task pair, participants viewed matrices formed by Xs and Os, and were asked to respond by pressing a button when they identified four Xs (from within a given matrix) that formed a square. The second task in the pair, which was performed simultaneously with the matrix task, required participants to listen to a series of high- and low-pitched tones, and respond when a tone was followed by another tone of the same frequency. Overall, HD participants were slower and less accurate than controls on choice reaction time (RT) tasks when administered within dual task contexts. Due to the different inputs, but same task outputs, it is difficult to draw conclusions on the Multiple Resources Theory. It is possible, and also endorsed by the authors, that this evidence points at a multi-dimensional system of semi-independent processes. More recent publications related to the notion of dual tasking are Thompson et al. (2010) and Mazzoni and Wexler (2009), but neither of these studies examine dual tasking as two different actions executed concurrently in response to two different tasks. In Thompson et al. (2010) they examined the execution of the same task (i.e., tapping) with one and two hands, and in Mazzoni and Wexler (2009) they examined two processes guiding the same action in a visuomotor task.

We extended past research by comparing two sets of dual tasks that differed in their degree of complexity. We have reported these tasks' combinations in published studies of dual tasking in healthy younger and older adults (Vaportzis, Georgiou-Karistianis, & Stout, 2013). Vaportzis et al. (2013) concluded that younger and older adults may adopt differential behavioural strategies depending on complexity and difficulty of dual tasks. The first task combination of this paradigm (termed the *simple* *dual task set)* paired simple choice RT with digit forward, and the second task combination (termed the *complex dual task set)* paired complex choice RT with digit backward. Choice RT tasks have been previously used to investigate dual task performance in HD, and have been found powerful for distinguishing between different patient groups (Jahanshahi, Brown, & Marsden, 1993). Previous studies have also found HD participants to be significantly impaired in digit forward and backward tasks (Beste, Saft, Güntürkün, & Falkenstein, 2008; Snowden, Craufurd, Thompson, & Neary, 2002; Wolf, Vasic, Schönfeldt-Lecuona, Ecker, & Landwehrmeyer, 2009). Digit forward and digit backward tasks are comparable, but differ in complexity. Digit forward requires passive storage of information, whereas digit backward requires participants to hold information in memory and perform an operation on it (Babcock & Salthouse, 1990).

For this study, we used dual tasks to examine the Multiple Resources Theory in HD. We selected a combination of tasks (i.e., choice RT and digit tasks) likely to be processed by separate modalities-responses (i.e., visual-manual and auditory-vocal), thus leading to minimal interference. However, we manipulated task difficulty within the dual task sets, by using easy and hard conditions for both the choice RT and digit tasks. We manipulated task difficulty because there is evidence suggesting that it induces resource allocation limitations, and thus dual task differences may emerge under harder conditions (Kahneman, 1973). In light of the Multiple Resources Theory, we predicted minimal interference between the dual tasks. However, consistent with past research we expected HD participants to be slower and less accurate across all task conditions compared with controls. Furthermore, we expected speed to be slower and error rates to be higher with increased task difficulty and from single to dual tasks across both groups. In keeping with the resource allocation account, we predicted disproportionate HD-related differences in speed and error rates in the complex dual task set, specifically that differences in the simple dual task set would support that simpler tasks make disproportionately high demands in HD.

Method

Participants

Thirteen participants in the early stages of HD and 13 healthy controls were included in this study. Healthy controls were recruited via word-of-mouth, online advertisements on the Monash University website, and retirement villages around Melbourne, and were group-matched to HD participants by sex, age and education. HD participants were recruited from an existing patient database. Participants were diagnosed by an experienced neurologist (AC) on the basis of genetic confirmation of the disease, and the unequivocal presence of motor symptoms associated with HD. Years of diagnosis prior to participation in this study ranged from 2 to 7. CAG ranged from 40 to 47. Motor symptom severity was rated using the motor scale of the Unified Huntington's Disease Rating Scale (UHDRS; Huntington Study Group, 1996). The range of scores in our sample was between 7 and 34, out of a possible 124 with greater scores indicating more impaired motor function. The Total Functional Capacity Scale of the UHDRS was also assessed. The range of scores in our sample was between 3 and 13 out of a possible 13 with greater scores indicating higher functioning. Sample characterisation measures included the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005), the Wechsler Test of Adult Reading (WTAR; Wechsler, 2001), and the Inventory of Depressive Symptomatology-Self-report (IDS-SR; Rush, Carmody & Reimitz, 2006). The MoCA is a 30-point cognitive screening test designed to detect cognitive impairment. The suggested cut-off point for mild impairment is 26 (Nasreddine et al., 2005). All control participants performed over 26 on the MoCA. The WTAR is a premorbid estimate of IQ, and is composed of 50 words that have irregular letter to sound translations. The IDS-SR is a 30-item questionnaire that assesses the severity of depression within the past 7 days for all symptom domains within major depression according to the Diagnostic and Statistical Manual-IV (American Psychiatric Association, 1994). A score of 0 indicates no depressive symptoms, whereas a score of 84 indicates very severe depressive symptoms. Education level was assessed based on the International Standard Classification of Education (ISCED) system, according to which 0 indicates pre-primary education and 6 second stage tertiary education (UNESCO, 1997). ISCED, WTAR and IDS-SR scores did not significantly ($p < .05$) differ between HD participants and controls; MoCA scores were significantly lower for HD participants, $t(23) = 2.90$, $p = .008$, $d = 1.18$.

Demographic and disease characteristics of participants are presented in Table 1. All participants gave written informed consent, were fluent in English, and self-reported that they were free of upper limb impairments (e.g., wrist injuries), and had normal or corrected-to-normal vision and hearing. Controls also self-reported that they were free of neurological disease and psychological disorders. Ethics approval was granted by the Monash University Human Research Ethics Committee.

INSERT TABLE 1

Task description

Participants were tested individually in a quiet room, and were instructed to perform all tasks as quickly and as accurately as they could. We used two sets of dual tasks: the simple dual task set paired simple choice RT with digit forward, and the complex dual task set paired complex choice RT with digit backward. Each task within each set had an easy and a hard condition.

We administered both choice RT tasks on a Lenovo ThinkPad® X61 (Morrisville, NC, USA) laptop running E-Prime software (Schneider, Eschmann, & Zuccolotto, 2002). The laptop was placed in front of the participants within comfortable reach. Participants responded on the keyboard to stimuli that were presented in the centre of the screen. They pressed the left arrow with their left index finger to respond to target stimuli, and the right arrow with their right index finger to respond to non-target stimuli. The ratio of target/non-target stimuli was similar. RT and error rates were recorded. RT was the time required from the moment each stimulus appeared on the screen until participant's response. Error rates were the percentage of incorrect responses across all trials. A correct response was recorded when participants responded with the designated keyboard arrow to a target or non-target stimulus.

In the *simple choice RT* task, stimuli were letters of the alphabet, some of which were designated as target letters, and the rest as non-target letters. The target letters were X and Z in the easy condition, and X, Z, O and Y in the hard condition. Non-target letters were other letters of the alphabet. Trials started with a "get-ready" sign (+) that remained on the screen for 250 ms. Then, a letter appeared in the same position, and until the participant responded or for up to 3000 ms (see Figure 1A). Because hard digit forward requires more time, we adjusted the number of simple choice RT trials so that there were enough trials to last throughout the hard digit task.

Therefore, there were 45 simple choice RT trials performed concurrently with easy digit forward and 54 trials performed concurrently with hard digit forward.

In the *complex choice RT* task, stimuli were 3 X 3 matrices of regular arrays of Xs and Os. In the easy condition, the target matrices had three Xs in a row, either horizontally or vertically. In the hard condition, they had either three Xs *or* three Os in a row (see Figure 1B). In non-target matrices, Xs and Os appeared in any location that did not constitute a row. Each stimulus was displayed on the screen until the participant responded or for up to 3000 ms. The interstimulus interval was 500 ms. The number of complex choice RT trials was 30 when it was performed concurrently with easy digit backward, and 40 when it was performed concurrently with hard digit backward.

INSERT FIGURE 1A AND 1B HERE

For *digit forward*, stimuli were 4-digit (easy) and 5-digit (hard) numbers, and for *digit backward*, stimuli were 3-digit (easy) and 4-digit (hard) numbers. Digits ranged between 0 and 9, and each digit appeared only once in any given number. The series of numbers was read out at a rate of approximately 1 s, and then participants had to repeat them aloud in the correct order. As soon as participants recalled a series, the researcher presented the following one. Error rates were recorded as the percentage of incorrect responses across trials. For the single tasks, participants completed 10 trials. For the dual tasks, the number of trials varied from participant to participant since the digit tasks ended once participants had finished the choice RT tasks.

For the dual task conditions, participants started the choice RT tasks by pressing the Enter button on the keyboard. At the same time, the experimenter started reading a series of numbers, the length of which depended on the condition (e.g., easy, hard). As soon as the participant recalled a series, the experimenter read out the following one.

Design

For each dual task set, participants first performed the four single tasks followed by every possible combination of the choice RT with digit tasks as described in Table 2. Participants performed practice trials prior to each of the single tasks only. The simple and complex dual task sets were two of four sets of tasks that participants performed as part of a larger study. The order of the four sets was counterbalanced across participants, and thus, half of the participants performed the simple dual task set first, whereas half of the participants performed the complex dual task set first. We did not counterbalance the order of the conditions, because a full permutation with all the different conditions for all the different sets of tasks was deemed impractical due to the large number of conditions within each set of tasks as well as the sample size. Furthermore, we wanted easy tasks to precede hard tasks in order to allow mastery of the easy task before increasing task difficulty. Similarly, we wanted single tasks to precede dual tasks in order to allow mastery of the single tasks before adding the challenge of a concurrent task.

INSERT TABLE 2

Statistical analyses

Trials with values more than 3.5 standard deviations from the individual mean were excluded prior to computing overall means and standard deviations for *RT* and *error rates* across all tasks; however, the percentage of the excluded trials was very small (< 2%). For each dependent variable, mixed model ANOVAs were used to examine effects of groups and task conditions. Taking for example the simple dual task set, 2 X 2 X 3 mixed model ANOVAs were computed separately for RT and errors rates, with Group as a between subjects factor (HD, controls), and two within factors: Simple Choice RT Task Difficulty (easy, hard), and Digit Forward Task Difficulty (none, easy, hard). The same model was used for the complex dual task set. We report Greenhouse-Geisser corrected degrees of freedom due to violations of the sphericity assumption when appropriate. Significant interactions of interest were followed with Bonferroni post hoc tests ($\alpha = .05$).

We also computed *dual task costs* separately for RT and error rates for the simple and complex choice RT tasks, as well as for error rates for the digit tasks, to assess performance costs associated with completing tasks concurrently. In line with past studies (de Ribaupierre & Ludwig, 2003; McDowd & Craik, 1988; Swanenburg, de Bruin, Hegemann, Uebelhart, & Mulder, 2010), we used the formula dual task cost = (single task-dual task)/single task to calculate the relative ratio of single task to dual task that controls for single task performance. Taking for example the simple dual task set, we used a 2 X 2 X 2 mixed-model ANOVA with the between factor Group (HD, controls) and two within factors: Simple Choice RT Task Difficulty (easy, hard) and Digit Forward Task Difficulty (easy, hard). We used the same model for complex choice RT and digit tasks. Negative dual task costs indicate that RT decreased and error rates increased in the dual tasks in comparison to the single tasks.

Results

Overall, HD participants were slower and less accurate on the choice RT tasks. In addition, performance of both groups was worse in the dual tasks compared with the single tasks. In this section, we first present the simple choice RT task performance (single and dual tasks) followed by the complex choice RT task performance (single and dual tasks). Finally, we present performance on the digit tasks.

Simple choice RT task performance

For the simple choice RT (single and dual tasks), slowing was associated with being in the HD group, performing dual tasks, and easy digit forward. Using RT as the dependent variable, a three-way ANOVA revealed significant main effects of Group, $F(1,24) = 8.19$, $p = .009$, $\eta^2 = .25$, with HD participants being significantly slower than controls, and Digit Forward, $F(1.54,37.04) = 51.25$, $p < .001$, $\eta^2 = .68$, with significantly slower performance in the dual tasks (easy and hard digit forward) compared with single tasks (no digit forward). Surprisingly, the easy digit forward conditions were performed significantly ($p < .001$) slower than the hard digit forward conditions. As there were no significant interactions, we did not find evidence that having HD unduly compromised performance of dual tasks compared to controls. However, the two-way interactions between Group and Simple Choice RT *and* Group and Digit Forward showed a trend towards significance ($p = .06$, $\eta^2 = .11$). HD participants were slower compared with controls and their performance deteriorated at the harder levels of the simple choice RT and digit forward tasks.

For error rates, a three-way ANOVA revealed that error rates were more affected by the difficulty level of the digit forward task in HD. Specifically, we found a significant main effect of Digit Forward, $F(1.60,38.39) = 16.33$, $p < .001$, $\eta^2 = .40$, and an interaction between Group and Digit Forward, $F(1.60,38.39) = 3.54$, $p = .04$, $\eta^2 =$

.13 (see Figure 2). Post hoc analysis showed that HD participants made significantly ($p < .05$) more errors in the dual tasks (easy and hard digit forward) compared with the single tasks (no digit forward).

For dual task costs, we did not find any interactions or HD-related differences for either RT or error rates suggesting that neither group was more susceptible to dual task demands. For dual task costs of *RT,* we found significant main effects of Simple Choice RT, $F(1,24) = 4.41$, $p = .04$, $\eta^2 = .15$, with significantly greater costs in the easy simple choice RT, and Digit Forward, $F(1,24) = 20.09$, $p < .001$, $\eta^2 = .45$, with significantly greater costs in the easy digit forward. For dual task costs of *error rates,* we found a significant main effect of Digit Forward, $F(1,24) = 8.93$, $p = .006$, $\eta^2 = .27$, with significantly greater costs in the hard digit forward conditions.

INSERT FIGURE 2 HERE

To investigate whether HD participants were more inclined to sacrifice speed for accuracy, we performed a series of correlational analyses between speed and error rates for each of the six simple choice RT conditions separately for the two groups. We found significant ($p < .05$) positive correlations across a number of conditions suggesting speed-accuracy trade-offs for the HD group only. Specifically, we found speed-accuracy trade-offs in all dual task conditions for HD participants. HD participants also showed speed-accuracy trade-offs in the hard simple choice RT task when the task was performed on its own. Contrary to HD participants, controls did not show speed-accuracy trade-offs in any of the simple choice RT conditions. (see Figure 3).

INSERT FIGURE 3

Complex choice RT task performance

For the complex choice RT (single and dual tasks), slowing was associated with being in the HD group, performing dual tasks, hard complex choice RT, and easy digit forward. Using RT as the dependent variable, a three-way ANOVA revealed significant main effects of Group, $F(1,24) = 6.03$, $p = .022$, $\eta^2 = .20$, Complex Choice RT, $F(1,24) = 13.88$, $p = .001$, $\eta^2 = .36$, and Digit Backward, $F(1.86,44.67) = 120.01$, $p < .001$, $\eta^2 = .83$. We also found a significant interaction between Group and Digit Backward, $F(1.86,44.67) = 6.66$, $p = .01$, $\eta^2 = .21$ (see Figure 4). Post hoc analysis showed that both groups were significantly ($p < .001$) slower in the easy digit backward conditions, compared with the hard digit backward and single task conditions; however, HD participants were significantly slower ($p < .001$) in the easy digit backward conditions compared with controls.

INSERT FIGURE 4 HERE

In addition, we found a significant interaction between Complex Choice RT and Digit Backward, $F(1.79,43.04) = 121.08$, $p < .001$, $\eta^2 = .46$. Post hoc analysis revealed that hard complex choice RT task was performed significantly ($p < .001$) slower than easy complex choice RT task in the single tasks only (no digit backward); there were no significant differences between easy and hard complex choice RT tasks in the dual task conditions (when complex choice RT tasks were performed with either easy or hard digit backward). We also found that the easy digit backward dual task conditions were performed significantly ($p < .001$) slower than the single tasks and the hard digit backward conditions regardless of complex choice RT difficulty.

For error rates, a three-way ANOVA showed that HD participants were less accurate. Specifically, we found a significant main effect of Group, $F(1,24) = 11.28$, $p = .003$, $\eta^2 = .32$, with HD participants making significantly more errors than controls. We also found a significant main effect of Digit Backward, $F(1.61,38.74) = 28.90$, $p < .001$, $\eta^2 = .54$, and an interaction between Complex Choice RT and Digit Backward, $F(1.93,46.45) = 4.61$, $p = .01$, $\eta^2 = .16$. Post hoc analysis showed that all participants made significantly ($p < .01$) more errors in the dual tasks (easy and hard digit backward) compared with the single tasks (no digit backward); however, there were significantly ($p = .008$) more errors in the hard complex choice RT when it was performed with hard digit backward rather than easy digit backward.

For dual task costs, we did not find any interactions or HD-related differences for RT; however, for error rates, we found that HD participants were less susceptible to dual task demands in the hard digit backward conditions. More specifically, for dual task costs for *RT,* we found significant main effects of Complex Choice RT, $F(1,24) = 44.71$, $p < .001$, $\eta^2 = .65$, with significantly greater costs in easy complex choice RT, and Digit Backward, $F(1,24) = 76.32$, $p < .001$, $\eta^2 = .76$, with significantly greater costs in easy digit backward. For dual task costs for *error rates,* we found a significant interaction between Group and Digit Backward, $F(1,24) = 6.15$, $p = .02$, $\eta^2 = .20$ (see Figure 5). Post hoc analysis showed that HD participants did not differ from controls on easy digit backward performance; however, HD participants had significantly ($p = .01$) lower dual task costs in the hard digit backward compared with controls.

INSERT FIGURE 5

Similarly with the simple choice RT tasks, we performed a series of correlational analyses between speed and error rates for each of the six complex choice RT conditions separately for the two groups. We found significant ($p < .05$) positive correlations across a number of conditions. Specifically, we found that HD participants sacrificed speed for accuracy in all dual task conditions, but not in the single task conditions. Controls showed speed-accuracy trade-offs only in the easy complex choice RT dual tasks (see Figure 6).

INSERT FIGURE 6

Digit tasks performance

Performance of the two groups did not differ on the digit forward tasks. For the digit backward tasks, however, HD participants made significantly more errors. Specifically, for *digit forward*, a three-way ANOVA revealed a significant main effect of Digit Forward, $F(1,24) = 21.48$, $p < .001$, $\eta^2 = .47$, with significantly more errors in the hard conditions. There was also a significant main effect of Simple Choice RT, $F(1.78,42.73) = 10.44$, $p < .001$, $\eta^2 = .30$, with significantly more errors in the dual tasks compared with the single tasks. There were no significant interactions.

For *digit backward*, a three-way ANOVA showed significant main effects of Group, $F(1,24) = 4.82$, $p =.0.3$, $\eta^2 = .17$, with HD participants making significantly more errors than controls; Digit Backward, $F(1,24) = 50.47$, $p < .001$, $\eta^2 = .68$, with significantly more errors in the hard conditions compared with the easy conditions; and Complex Choice RT, $F(1.93,46.33) = 14.77$, $p < .001$, $\eta^2 = .38$, with significantly more errors in the dual tasks compared with the single tasks. There were no significant interactions. For dual task costs, we did not find any interactions or HD-related differences for either digit forward or digit backward. Despite the absence of any interactions, the three-way interactions between Group, Complex Choice RT and Digit Backward for errors rates and also dual task costs for error rates showed a trend in the direction of significance (p = .055, η^2 = .12). HD participants made more errors and had greater dual task costs than controls across all conditions; their performance deteriorated when hard backward digit was performed with hard complex CRT.

Discussion

This study examined whether simple tasks make disproportionately high demands in HD compared with controls, and tested the Multiple Resources Theory. We employed two dual task sets that varied in difficulty and complexity, and expected HD participants to be slower and less accurate across all conditions compared with controls.

In line with our prediction, and consistent with Sprengelmeyer et al. (1995) and Müller et al. (2002) we found that HD participants were overall slower. However, although they maintained similar levels of accuracy with controls in the simple choice RT tasks, their accuracy decreased in the complex choice RT tasks. Therefore, performance in HD was more compromised in the more demanding dual task set. Thompson et al. (2011) demonstrated impaired automaticity in HD using tapping tasks, and suggested that the automaticity principle extends to cognitive tasks as they found tapping variability to be correlated with neuropsychological measures, such as the Stroop test. We argue that difficulty in automatising responses in HD would be manifest by greater impairments in the simpler, less demanding tasks, whereas greater impairments in the more complex and demanding tasks, suggest attentional impairments in HD. We found that HD participants were more compromised in the more challenging dual task set, thus our findings are in keeping with the attentional impairment hypothesis.

In support of the Multiple Resources Theory, we expected minimal interference between the choice RT and digit tasks. Overall, our findings showed some resource sharing between two seemingly different tasks, suggesting that the visual and auditory modalities *and* the manual and vocal responses are not as utterly separate as the Multiple Resources Theory posits. Although not conclusively, these results may be explained by the Unitary Resource Theory as we found that with increased task difficulty performance of both groups deteriorated. Performance of HD participants was slower, possibly because they came to a point where attentional resources were not enough to perform the tasks quicker than controls. However, we found HD-related differences in error rates only in the complex choice RT tasks. Thus, our study highlights the importance of manipulating task difficulty and complexity, as well as taking into account speed and accuracy measures, as the relationships between HD and these measures may vary with task difficulty and complexity.

The Unitary Resource Theory suggests that *resource* is a general information processing capacity of the brain that can be shared when dual tasking in a graded way. Dual task interference may occur when two tasks exceed the amount of this limited resource. Support for this theory has come from neuroimaging studies that have shown dual tasks to activate overlapping brain regions, such as the lateral prefrontal cortex, to a greater degree than the same tasks performed on their own (Adcock, Constable, Gore, & Goldman-Rakic, 2000; Bunge, Klingberg, Jacobsen, &

Gabrieli, 2000; Klingberg, 1998). These findings suggest that dual task interference occurs due to a competition for the same processing resources between the two tasks with the lateral prefrontal cortex being a possible locus for this competition. HD results in neurodegeneration of several brain regions, including the lateral prefrontal cortex (Georgiou, Bradshaw, Phillips, Bradshaw, & Chiu, 1995; Poudel et al., 2013; Thiruvady et al., 2007; Wolf et al., 2008). Reduced level of functioning in the lateral prefrontal cortex may limit the availability of the attentional resource proposed by the unitary resource account. This is likely to be more evident during dual task performance, which requires concurrent information processing of multiple sources and higher loads of cognitive processing. Therefore, greater dual task interference in HD participants, compared with controls, may reflect decreased neural efficiency and therefore reduced cognitive capacity. It is important to note that despite the evidence that the lateral prefrontal cortex has an important role in dual task performance and interference, the underlying neuronal mechanisms remain elusive and more research is warranted. Both groups were slower and made more errors in the choice RT tasks when they performed the digit tasks concurrently, strengthening the notion that the dual task conditions increased cognitive load. Surprisingly, we found that HD participants had *lower dual task costs* in *error rates* when *complex choice RT* was performed with *hard digit backward,* and this was the only significant group difference that we found in dual task costs. We suggest that perhaps HD participants were more robust to the demands of the second concurrent task because their performance was already sufficiently compromised in the single task conditions, therefore, making it possible for them to incorporate the second task without further reduction in their accuracy.

Furthermore, we found that HD participants were more inclined to speed-accuracy trade-offs probably due to inability to maintain speed at reasonable accuracy and vice versa, and despite our instructions that emphasised both. This finding may be explained by accumulator models of speed-accuracy trade-offs. Accumulator models posit that sensory evidence accumulates over time from stimulus onset until a decision threshold (Ivanoff, Branning, & Marois, 2008). Speed-accuracy trade-offs may surface depending on the task and individual differences, and therefore, accumulation of evidence may progress more or less slowly and accurately (Ivanoff et al., 2008). Studies have suggested that speed-accuracy trade-offs are implemented by a prefrontal network (Ivanoff et al., 2008; Romo & Salinas, 2003), which has also been implicated in HD (Gray et al., 2013; Thiruvady et al., 2007; Wolf et al., 2008; Wolf, Vasic, Schönfeldt-Lecuona, Landwehrmeyer, & Ecker, 2007). It remains to be determined whether the different pattern of results between the two groups can be modulated by instructions that emphasise either speed or accuracy of performance.

In terms of the caveats of our study, our sample size was relatively small, and therefore, absence of significant interactions may be due to low power. However, some interactions (e.g., when error rates or dual task costs for error rates were used as dependent variables in the digit backward tasks) were close at approaching statistical significance, suggesting that significant interactions may emerge with a larger sample. The current findings warrant future investigation with a larger sample size that will supply adequate statistical power for interaction effects. To identify a target sample size necessary for detecting the expected interactions, we conducted post hoc power analyses using the program G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) with alpha at .05 and power at the recommended .80 level (Cohen, 1988). The analysis indicated that a total sample of 158 participants would be needed to detect a medium effect for a two-way interaction with group being one of the variables; 64 participants would be required to detect a large effect. With alpha at .10, analysis indicated that a total sample of 125 and 50 participants would be needed to detect a medium and large effect respectively. Although the power of our study was relatively low, we think that our data provide important and useful information that may be used by future studies to determine the strength and replicability of our findings. Due to the difficulty and expense of getting large samples of HD patients, small studies like this one, play an essential role in providing initial evaluation of tasks in HD, which can then be prioritized for future study.

Although we instructed participants to perform the tasks as quickly and as accurately as they could, our results suggest that it is likely that HD participants were affected differently than controls with respect to the competing goals of speed and accuracy. An important question that remains is whether the speed-accuracy trade-offs that we observed were a result of conscious rather than automatic processes. Furthermore, our conclusions must be considered in light of possible order effects since, for practical reasons, we did not counterbalance single and dual tasks. However, because we found that participants' performance deteriorated in the harder tasks, which were presented later (i.e., with the greatest amount of practice), if anything, counterbalancing would most likely have further strengthened our findings. In addition, a possible explanation for some of our results could be that some tasks were too easy for the control group (their range of scores was limited), and much harder for the HD group. As seen in Figure 3, for *single* tasks, between 21% and 35% of controls performed without error, suggesting that these tasks were too easy for them. Because our focus was on *dual* task performance, however, specific levels of performance on single tasks were of less concern. Rather, because combining two tasks is more challenging for participants, we prioritised having single tasks that were not too challenging on their own to be suitable in combination with a second task. For our dual task conditions, the maximum percentage of perfect scores was always below 15%, and in fact, for the harder dual task combinations, no participants performed perfectly, suggesting that the dual task conditions provided a meaningful range of difficulty suited to our purposes. Finally, our control group did not execute the simple choice RT dual tasks as efficiently as the single tasks, suggesting that even this simple combination of tasks placed some demand on conscious attention, and could not be entirely automatised.

A major aim of the current study was to compare different sets of dual tasks that differed in complexity. We also manipulated task difficulty of both tasks within each set. Research in dual tasking in HD is limited, and most previous studies have used only one dual task, and did not examine dual task performance at different difficulty levels. We found that HD participants were slower across all tasks, however, accuracy differences emerged with increased task complexity, suggesting some attentional impairment in HD. These findings, along with our results indicating speed-accuracy trade-offs mainly for HD participants, highlight the importance of taking into account measures of both speed and accuracy. Despite that, HD participants did not show greater dual task costs than controls; in fact, they showed lower costs in error rates of the complex choice RT task when performed with hard digit backward. Overall, we found a differential effect of dual task performance between HD participants and controls that depends on both the difficulty and complexity level of dual tasks. Although we did not support the Multiple Resources Theory, performance of both groups deteriorated with task difficulty giving some support to the Unitary

Resource Theory, and also with task complexity, giving support to the attentional impairment hypothesis in HD. Further investigation in dual tasking in HD is warranted as it is vital for independent living.

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Table 1

Demographic data for HD participants and controls

	HD n = 13	Controls n = 13
Sex (F:M)	4:9	4:9
Age (years)	58.15 (9.23)	55.31 (11.36)
MoCA	25.31 (2.62)	27.83 (1.52)
WTAR	109.46 (6.70)	111.25 (7.68)
IDS-SR	13.83 (7.49)	10.46 (5.22)
ISCED	4.15 (0.80)	4.54 (1.05)
Disease duration (years)	4.46 (1.94)	---
UHDRS Total Functional Capacity	10.08 (3.17)	---
UHDRS Motor score	21.42 (9.15)	---
CAG repeat	42.42 (1.92)	---

Note. CAG: Cytosine-adenine-guanine trinucleotide repeat; IDS-SR: Inventory of Depressive Symptomatology-Self-Report; ISCED: International Standard Classification of Education; MoCA: Montreal Cognitive Assessment; UHDRS: Unified Huntington's Disease Rating Scale; WTAR: Wechsler Test for Adult Reading.

Table 2

Study design

Order	Simple Dual Task Set	Hard Dual Task Set
1	Simple Choice RT E	Complex Choice RT E
2	Simple Choice RT H	Complex Choice RT H
3	Digit Forward E	Digit Backward E
4	Digit Forward H	Digit Backward H
5	Simple Choice RT E + Digit Forward E	Complex Choice RT E + Digit Backward E
6	Simple Choice RT E + Digit Forward H	Complex Choice RT E + Digit Backward H
7	Simple Choice RT H + Digit Forward E	Complex Choice RT H + Digit Backward E
8	Simple Choice RT H + Digit Forward H	Complex Choice RT H + Digit Backward H

Note. RT: Reaction time; E: Easy; H: Hard.

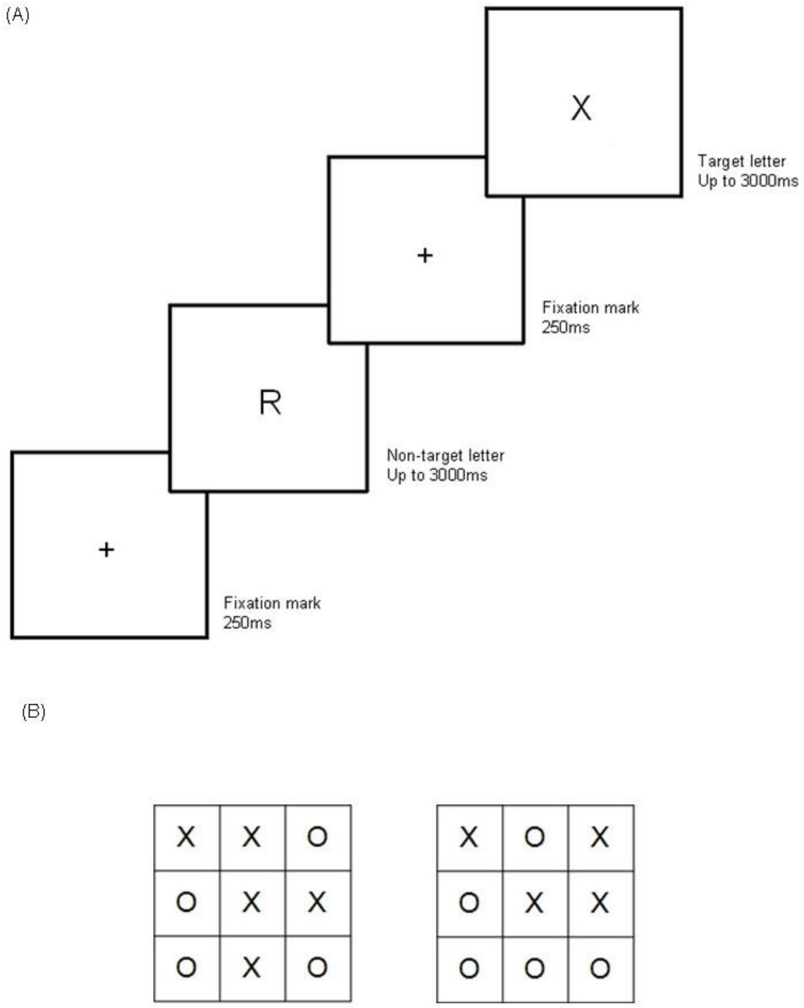

Figure 1. (A) A non-target (R) and a target (X) trial of the simple choice RT task. (B) Target stimuli of the complex choice RT task conditions. On the left matrix, three Xs appear in a row (easy or hard conditions); on the right matrix, three Os appear in a row (hard condition).

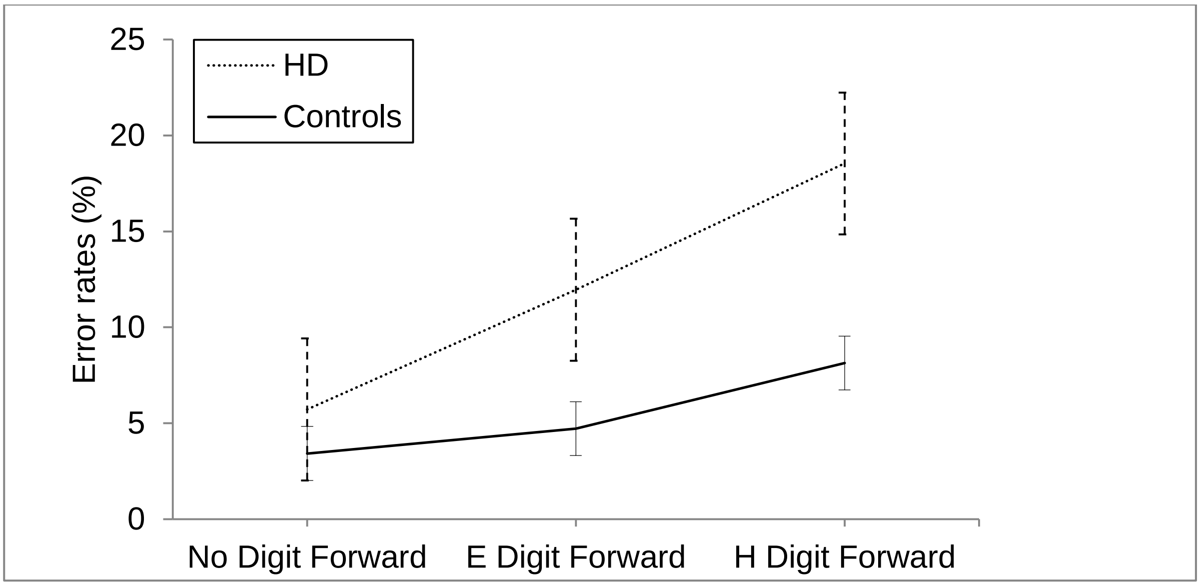

Figure 2. Error rates on the Simple Choice RT as a function of Group (HD, controls) and Digit Forward Task Difficulty (none, easy, hard). E: Easy; H: Hard. Standard error bars are included.

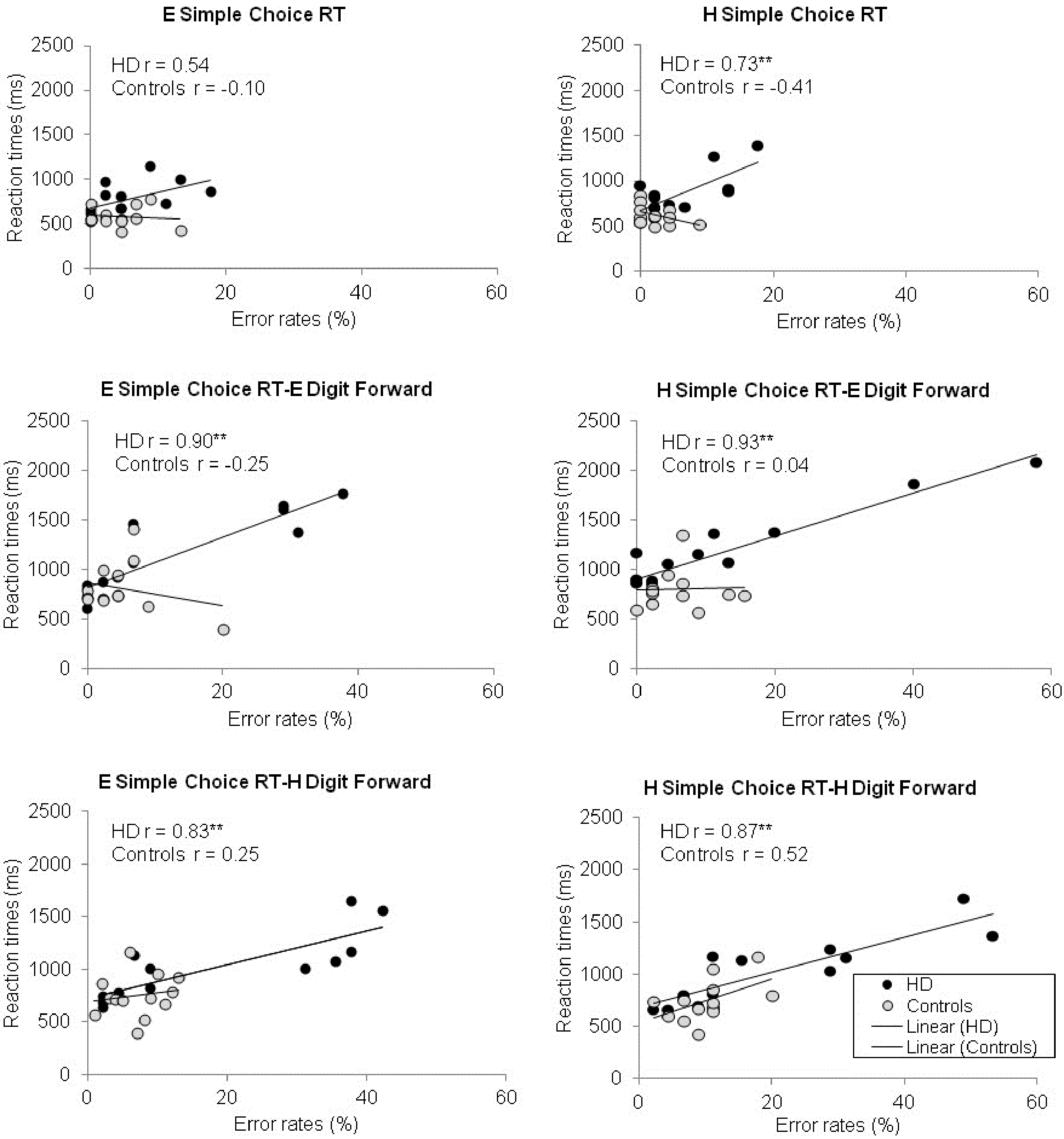

Figure 3. Speed-accuracy trade-offs for HD participants and controls across all conditions of the simple dual task set. ** $p < .001$.

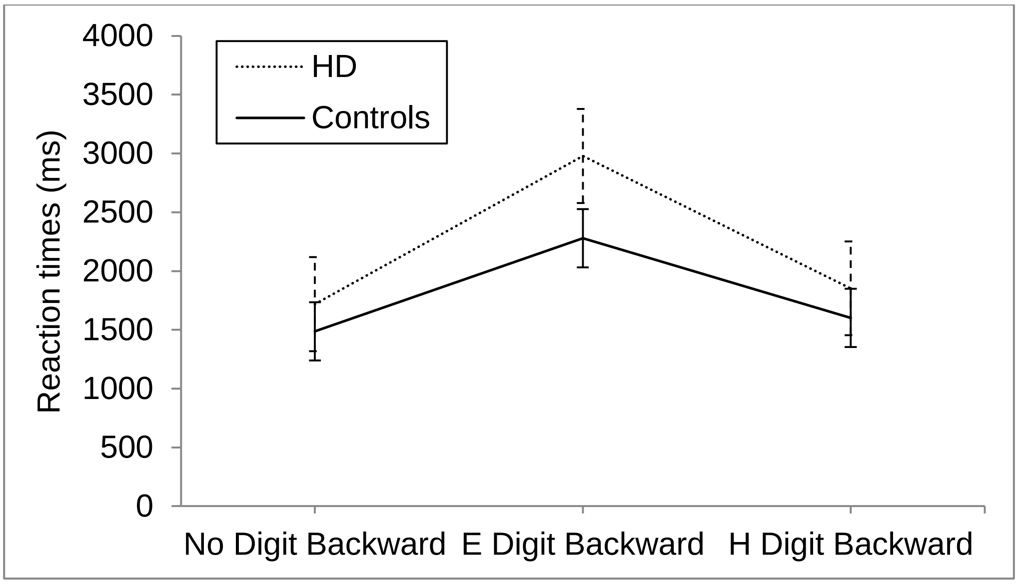

Figure 4. Reaction times on the Complex Choice RT as a function of Group (HD, controls) and Digit Backward Difficulty (none, easy, hard). E: Easy; H: Hard. Standard error bars are included.

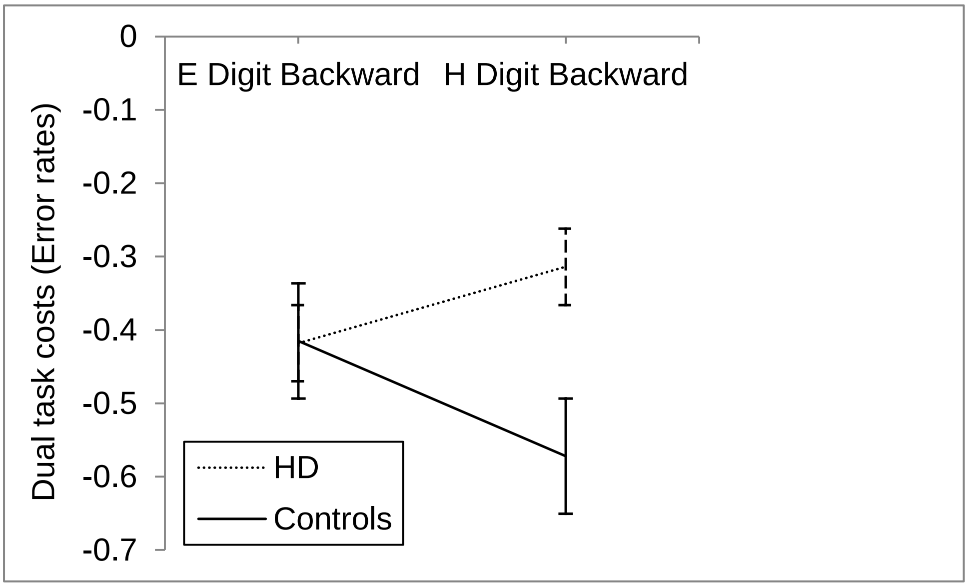

Figure 5. Dual task costs (error rates) on the Complex Choice RT (easy, hard) as a function of Group (HD, controls). E: Easy; H: Hard. Standard error bars are included.

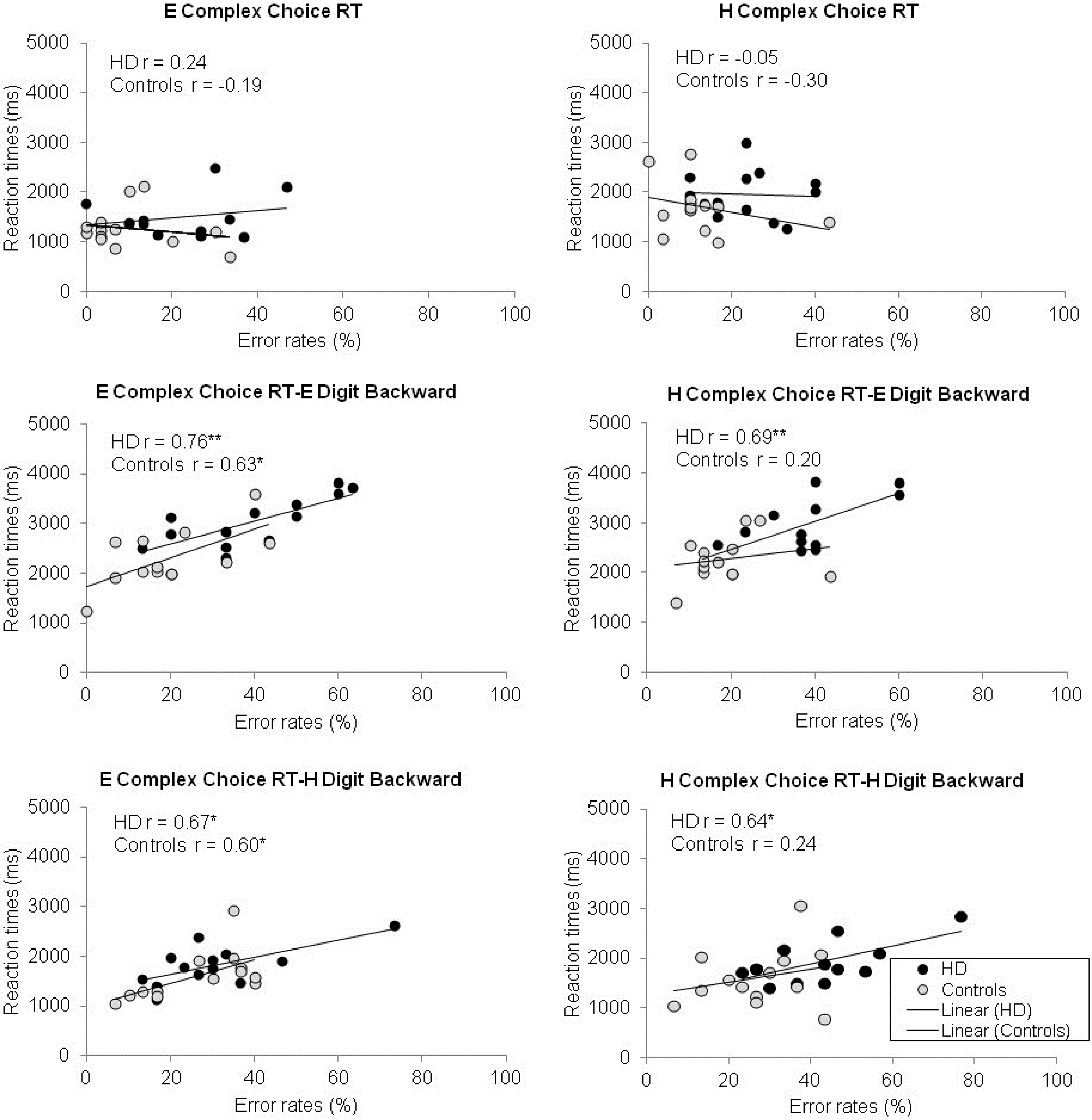

Figure 6. Speed-accuracy trade-offs for HD participants and controls across all conditions of the complex dual task set. * $p < .05$; ** $p < .001$.