

## **Spatiotemporal analysis of multi-stroke drawing movements in Parkinson's disease reveals an impaired speed-accuracy tradeoff.**

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Parkinson's disease impairs basic motor functions such as tone and speed of movement via a dopaminergic deficiency in motor circuits that has been elucidated in remarkable detail. But how these "low level" motor deficits lead to impairment in writing, drawing and higher level measures of motor function is much less clear. Micrographia is a frequent complaint for many patients with PD, but observations about micrographia are often based on tests with pen and paper, where the temporal features of handwriting cannot be determined. In general, micrographia might be produced by maintaining movement speed but with reduced duration, or by maintaining movement duration, but with reduced speed. Here we examined handwriting in PD under conditions in which we could dissociate these possibilities.

Methods: 21 PD participants and 16 demographically similar controls underwent testing. PD participants all met the UIK Parkinson's disease Society brain bank diagnostic criteria and were Hoehn and Yahr stage 1.5-3 (moderate stage). Participants were tested while on their standard medication regimen. The task involved presentation of a visual stimulus of a square on the tablet, then having the participant replicate the square by drawing with a stylus in a different position on the screen. In particular, we had patients and demographically similar controls draw virtual squares using a handheld pen-shaped stylus on the display surface of a computer tablet (Wacom Cintiq) where the writing could be displayed in real time. Critically, this allowed us to accurately record both the spatial and temporal features of the movement. We had patients either draw static squares at a self-determined pace or attempt to match the content and timing of animations showing sample drawings of squares at various speeds ranging from 55-230mm/s.

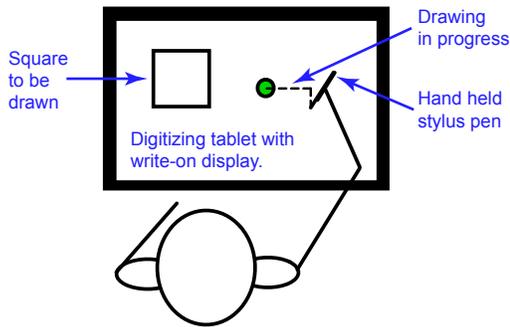
To examine the spatiotemporal features of the square drawing task, we quantified impairments in the size, speed, and accuracy of movement, as shown in Figures 2 and 3. We developed an algorithm for the automatic segmentation of each square into four submovements to facilitate the measurement of size and speed for each side of the square. These measurements were averaged for each drawing. We also developed a quantitative measure of dynamic inaccuracy that quantified the total amount of off-axis movement during each stroke. This measure was simultaneously sensitive to skewed and curved strokes and was accumulated over each drawing. Here we compared the effects of different measures by computing the "Cohen's d" effect size ( $(\mu_1 - \mu_2) / \sigma$ ).

Results: The on-medication PD patients we studied displayed statistically significant deficits in all three of these features. However, the deficits in size and speed were only moderate, with mean effect sizes across conditions of 0.42 and 0.59, respectively (see Figure 2), whereas the deficits in accuracy were more severe with a mean effect size of 1.11 (Figure 3b). Remarkably, when the effects of speed and accuracy were combined in the speed matching task data by comparing the accuracy for movements matched based on their actual speeds (Figure 3c) rather than on the prescribed speed (Figure 3b), we found an average effect size of 1.63, with a value of 2.23 for the fastest speed-matched movements.

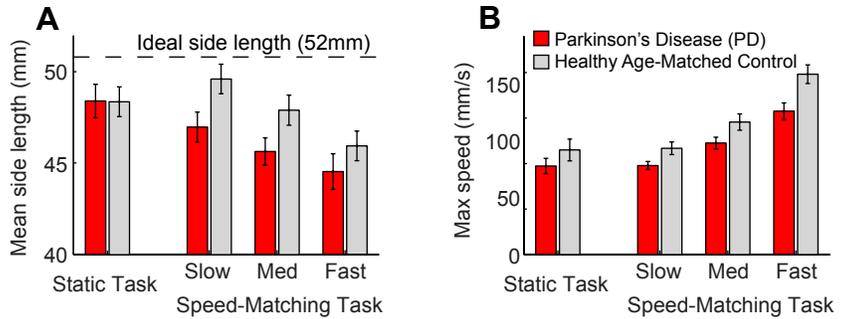
These findings suggest that moderate-stage, on-medication PD patients display smaller deficits in the size and speed of multi-stroke drawing movements than in the accuracy of those movements, especially when accuracy is compared at the same speed. Moreover, the increase in the effect size from 1.03 to 2.23 when comparing speed-matched slower and faster speed matched movements in Fig 3c suggests that PD patients display a notable decrement in accuracy relative to controls as speed increases, which amounts to a steeper speed-accuracy tradeoff.

To further investigate this possibility, we estimated the sensitivity of the speed-accuracy relationship in individual subjects by performing principle components analysis (PCA) on the relationship between speed and accuracy across all individual drawings in individual subjects, as illustrated in Figure 4a. We used the slope of the first principle component as a measure of the speed accuracy sensitivity rather than linear regression, as the latter is known to consistently underestimate the slope of the relationship between two variables if the "independent variable" is not entirely noise free. An example showing the individual movement data from a single PD patient and a single healthy control participant is illustrated in Figure 4a, and the group data is presented in Figure 4b. This analysis revealed increased speed-accuracy sensitivity across individual trials in the data from individual PD patients ( $p < 0.01$ ). This finding is especially interesting, as recent work has demonstrated a preserved speed-accuracy tradeoff in simple point-to-point reaching arm movements (Krakauer & Mazzoni, 2007). The variance between these results suggests that the increased motor complexity of the multi-stroke drawing movements in our study may be responsible for the speed-accuracy tradeoff deficit that we observe. Another possibility is the more distal nature of the drawing movements in our study, which rely on motion in the wrist and fingers rather than the elbow and shoulder. Further work is clearly needed to fully delineate the dysfunctional mechanisms underlying these differences; however, the large effect sizes that we are able to demonstrate when comparing a quantitative measure of dynamic accuracy across matched speeds suggests that spatiotemporal analysis of drawing and handwriting movements in PD may harbor significant diagnostic value.

**Figure 1: Experiment Setup**

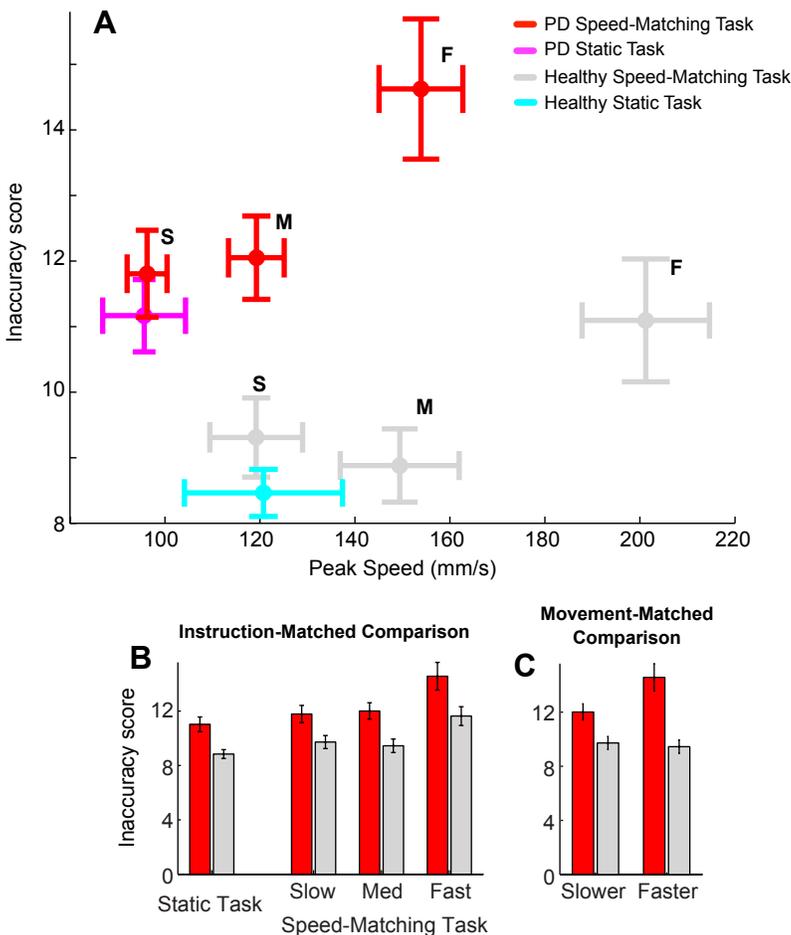


**Figure 2: Size and Speed Comparison During Square Drawing Task**



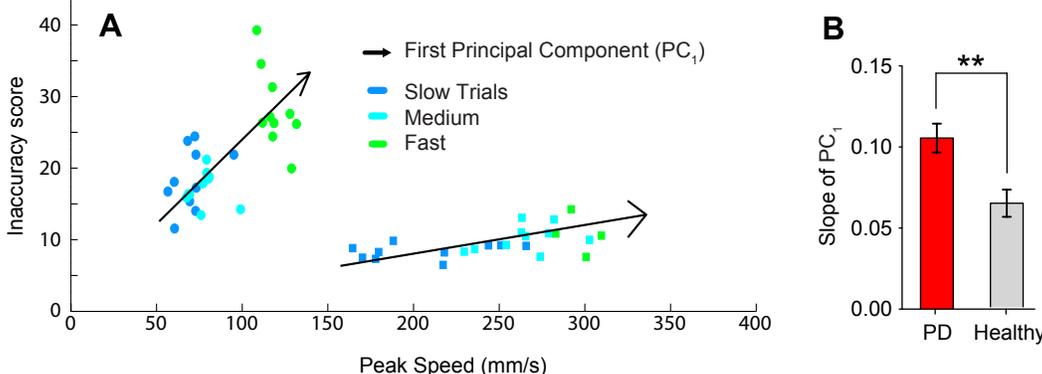
**Figure 2:** Side length and segment speed in the square drawing task. (A) A 2-way ANOVA shows significant effects of speed and group, with PD patients and faster speeds associated with shorter movements, but no interaction between these factors. (B) A 2-way ANOVA shows significant effects of speed and group, as well as a significant interaction between these factors, with PD patients and faster speeds associated with slower movements.

**Figure 3: Comparison of Speed and Accuracy**



**Figure 3:** Dynamic inaccuracy measure (see methods) as a function of movement speed. (A) A scatter plot of accuracy versus speed. The letters S, M, & F on the plot label Slow, Medium, & Fast-Instructed movements, respectively. Note the generally increased inaccuracy score in PD patients (red & purple) as well as the increased speed sensitivity that this score displays in PD. (B) Comparison of inaccuracy scores between patients and controls based on task instructions. (C) Comparison of inaccuracy scores between patients and controls based on actual rather than instructed movement speed. Note that the slower speed-matched movements in PD are already significantly more inaccurate than controls ( $p < 0.01$ , effect size = 1.03), however the faster speed-matched movements in PD show an even greater effect, with double the effect size ( $p < 0.0001$ , effect size = 2.23).

**Figure 4: Individual Subject Speed Accuracy Tradeoffs**



**Figure 4:** Speed-Accuracy tradeoffs within individual subject data. (A) Example data showing a PD patient with a steeper speed-accuracy sensitivity than a control subject. (B) Group averaged slopes that characterize the steepness of the speed-accuracy tradeoff show increased sensitivity in PD patients ( $p < 0.01$ ).