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Title

Impaired touchscreen skills in Parkinson's disease and effects of medication

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Abstract

***Background*:** Deficits in fine motor skills may impair device manipulation including touchscreens in people with Parkinson's disease (PD).

***Objectives*:** To investigate the impact of PD and anti-parkinsonian medication on the ability to use touchscreens.

***Methods*:** Twelve PD patients (H&Y II-III), OFF and ON medication, and 12 healthy controls (HC) performed tapping, single and multi-direction sliding tasks on a touchscreen and a mobile phone task (MPT). Task performance was compared between patients (PD-OFF, PD-ON) and HC and between medication conditions.

***Results*:** Significant differences were found in touchscreen timing parameters, while accuracy was comparable between groups. PD-OFF needed more time than HC to perform single ($p = 0.048$) and multi-direction ($p = 0.004$) sliding tasks and to grab the dot before sliding (i.e. transition times) ($p = 0.040$; $p = 0.004$). For tapping, dopaminergic medication significantly increased performance times ($p = 0.046$) to comparable levels as those of HC. However, for the more complex multi-direction sliding, movement times remained slower in PD than HC irrespective of medication intake ($p < 0.050$ during ON and OFF). The transition times for the multi-direction sliding task was also higher in PD-ON than HC ($p = 0.048$). Touchscreen parameters significantly correlated with MPT performance, supporting the ecological validity of the touchscreen tool.

***Conclusions*:** PD patients show motor problems when manipulating touchscreens, even when optimally medicated. This hinders using mobile technology in daily life and has implications for developing adequate E-health applications for this group. Future work needs to establish whether touchscreen training is effective in PD.

Dopaminergic depletion in the basal ganglia, the main deficit underlying Parkinson's disease (PD), results in a variety of symptoms.[1] While loss of manual dexterity significantly impairs activities of daily living,[1,2] it has received less research attention in comparison to gait and balance problems. Poor manual dexterity may affect the use of touchscreens to operate mobile devices, which are an integral part of daily life. Furthermore, the interest in touchscreen applications to monitor disease progression or training programs is growing in PD.[3] Here, we aim to investigate the specific problems with touchscreen manipulations. Increasing the understanding of these deficits will inform the design of specific training interventions to improve touchscreen skills, so that people with PD are able to participate in using mobile technology.

Recent work revealed slower performance when using a smartphone application, including tapping and sliding movements, in PD patients with a higher score on the motor part of the Movement Disorders Society Unified Parkinson's Disease Rating scale (MDS-UPDRS-III).[4] Interestingly, 40% of patients reported to experience difficulties with the application due to 'hand clumsiness'.[4] Also, deficits in manual dexterity impeded the use of touchscreen devices in PD.[5] Both studies included patients ON medication without a comparison with healthy controls (HC). Recent research demonstrated that slower performance and higher numbers of tapping errors on a smartphone discriminated PD patients ON medication from HC[6] as well as slower speed to type a telephone number on a smartphone.[7]

As for the effects of medication on upper limb skills, some studies showed a faster performance and improved movement vigor[8], though at a cost for movement accuracy.[9,10] Others found no beneficial effects.[2] For touchscreen skills specifically, Wissel et al.[11] revealed that improved tapping frequency and decreased tapping accuracy could distinguish between ON and OFF medication in PD.

Given these inconsistent effects and the fact that few studies investigated the impact of PD and medication on touchscreen skills, we developed a test battery involving tasks with a greater variety of motor demands than merely tapping, such as grabbing and sliding movements. Based on the literature, we hypothesized that touchscreen skills would be compromised in PD patients compared to age-matched HC and that dopaminergic medication would result in invigoration of movement, i.e. an improvement of timing parameters, but not necessarily a more accurate performance.

Methods

Participants

Fourteen PD patients and 12 age-matched HC were recruited from the database of the Department of Rehabilitation Sciences, KU Leuven, Belgium. Inclusion criteria for PD patients consisted of Hoehn and Yahr (H&Y) stage I-III[12], a PD diagnosis according to the United Kingdom PD Society Brain Bank criteria[13] and right handedness, measured by the Edinburgh Handedness Inventory.[14] Exclusion criteria for all participants were: Mini-Mental State Examination (MMSE) < 24 [15], neurological disorders besides PD and upper limb deficits unrelated to PD that might interfere with task performance. This study was approved by the local Ethics committee UZ/KU Leuven according to the code of Ethics of the World Medical Association (Declaration of Helsinki, version 2013, S61793). Prior to participation in the study, an informed consent form was signed after explanation of the study protocol.

Experimental procedure

This study consisted of one session, either in a quiet room at the Department of Rehabilitation Sciences of KU Leuven or at the participant's home. First, PD patients performed an extensive

93 motor assessment OFF medication in the morning, between 12 and 15 hours after medication
94 intake. Tests included the MDS-UPDRS-III[16], the Purdue Pegboard test (PPT)[17] and a newly
95 developed test battery of touchscreen skills (see below). A visual analogue scale (VAS)
96 assessed fatigue experienced in hand/finger after each task of the test battery. Moreover, a
97 mobile phone task (MPT) measured the time needed to type a predefined telephone number
98 on a smartphone.[7] Subjects performed three trials of the MPT, each trial involving a different
99 number. The average of the second and third trial was calculated.
100 Next, patients took their normal dose of medication. In the period between intake and
101 optimal functioning of dopaminergic medication (±1 hour), a number of questionnaires were
102 administered. These included the dexterity questionnaire (DEXTQ-24)[18] and the Hospital
103 Anxiety and Depression Scale (HADS).[19] Cognition was examined with the Montreal Cognitive
104 Assessment (MoCA)[20] and the Trail Making Test (TMT).[21] The Mobile Device Proficiency
105 Questionnaire (MDPQ-16)[22] and smartphone specific questions (see **Supplementary**
106 **Appendix**) assessed daily smartphone use. Further, a medication anamnesis was taken,
107 allowing the calculation of the levodopa equivalent daily dosage (LEDD).[23,24] Finally, PD
108 patients repeated the motor assessment in ON, when their medication was working
109 optimally. The same experimental procedure was applied in HC, but without administering
110 medication and the PD-specific assessments and questionnaires.

111 **Test battery of touchscreen skills**

112 A test battery of touchscreen skills, consisting of three tasks, was developed on a touch-
113 sensitive tablet (HP Elite x2 1012 G2 Hybrid Notebook) using a graphical programming
114 environment with LabVIEW Software (version 18.0f2, National Instruments, Austin, TX, USA).
115 The tapping task required participants to tap between two dots, 200 pixels apart, starting with

116 the left dot (**Fig 1**, Tapping). Three trials of 30 repetitions were completed. In the single sliding
117 task, subjects had to slide a dot over a distance of 500 pixels to a predefined target from left
118 to right (**Fig. 1**, Single Slide). This sliding movement was repeated 30 times during three trials.
119 During the more complex multi-direction sliding task the starting position of the dot randomly
120 varied between four positions: 300 pixels to the 1) left, 2) right, 3) above or 4) below the
121 target (**Fig. 1**, Multi Slide). This was repeated for three trials of 32 repetitions, i.e. 8 slides in
122 each direction. The size of the dots and the blue square were kept consistent throughout the
123 session, i.e. 50x50 pixels and 100x100 pixels respectively. All tasks were performed as fast
124 and accurately as possible with the right index finger. Considering the test battery was new,
125 a repeatability analysis was performed (**Supplementary Material S1)**.

126 **Outcome measures**

127 Both timing and accuracy parameters were automatically recorded by the custom-made
128 application with a temporal resolution of 1 ms and a spatial resolution of 0.135 mm. For the
129 sliding tasks, timing parameters included the total sliding time (ms), i.e. the time necessary to
130 perform a separate sliding movement. The transition time (ms) involved the time in between
131 these sliding movements. Onset was defined as the moment of releasing the dot and
132 termination was determined as the moment of grabbing the next dot on the screen. Accuracy
133 parameters for the sliding tasks, consisted of the error distance (pixels), measuring the
134 deviation between the target center and the actual release point, as well as the number of
135 correct responses (%), i.e. if the dot was released within the predefined target or not. For the
136 tapping task, timing parameters consisted of the inter-tap interval time (ms), defined as the
137 time in between tapping movements. To measure tapping accuracy, the number of correct

tapping movements (%), i.e. inside the green dot, was collected. For all tasks, the first repetition of each trial was excluded from the analysis.

Statistical analyses

Statistical analysis was conducted with SPSS software (version 24 SPSS, Inc., Chicago, IL, USA) with a significance level of $\alpha < 0.05$. Data distribution was assessed using Shapiro-Wilk tests and Q-Q plots. Depending on the normality of the distribution, independent t-tests or Mann-Whitney U tests compared PD-OFF with HC and PD-ON with HC. A Chi-squared test compared gender distribution between groups. Paired t-tests or Wilcoxon tests contrasted medication conditions. Also, a non-parametric McNemar test examined H&Y stages between medication groups. We also calculated an upper limb score of the MDS-UPDRS-III between medication conditions, consisting of item 3.3 to 3.6 and 3.15 to 3.18 (if item 3.17 for left or right arm was ≥1). For each comparison, we corrected for the different parameters per task using a Bonferroni method for multiple testing. The corrected P-values and effect sizes are reported. A non-parametric effect size estimate *r* was calculated using the formula: $r = z / \sqrt{N}$ (z= Z-score and N= number of observations). Effect size estimates range from -1 to +1 with values further away from zero indicating larger effect sizes (i.e. ±0.1, ±0.3 and ±0.5 representing small, medium and large effect sizes, respectively).[25,26] Exploratory correlation analyses were performed between the timing parameters and clinical characteristics (age, Purdue Pegboard Test, DEXTQ-24, MDS-UPDRS-III, MDS-UPDRS-III items 15a, 16a and 17a, MoCA, TMT, HADS) and between timing parameters and daily smartphone performance (MDPQ-16, MPT). Spearman correlations were performed across groups and significant correlations ($p < 0.05$) were repeated for both groups separately (PD-OFF and HC).

Results

Participants

Clinical characteristics are displayed in **Table 1**. Twelve PD patients and 12 HC completed the study. Two patients were excluded: One patient had already taken the morning dose of medication upon arrival and one was discontinued due to ill-health. Other incomplete data related to left upper limb task execution, were found in two patients mostly due to fatigue. PD patients and HC did not differ significantly (**Table 1**), except for a higher HADS-Depression score in PD patients ($p = 0.002$). In general, PD-OFF patients had worse upper limb skills than HC, reflected by the DEXTQ-24, Purdue Pegboard Test and MPT ($all\ p < 0.050$) (for MPT performance see **Suppl. Fig 2**). Dopaminergic medication improved disease severity, indicated by the lower MDS-UPDRS-III score and upper limb scores ON compared to OFF medication ($\text{both}\ p = 0.003$). However, there were no significant medication effects on the Purdue Pegboard Test or the MPT ($p > 0.050$). Importantly, tremor in the right upper limb was generally low and did not improve with dopaminergic medication ($p > 0.100$), apart from the kinetic tremor ($p = 0.046$).

Tablet task performance

In the **Supplementary Material S1**, we report on the repeatability analysis showing some learning from trial 1 to trial 3 for timing parameters, though without effects on the analysis of the pooled results.

Effect of PD

Table 2 and **Figure 2** reveal that PD-OFF performed both sliding tasks significantly slower compared to HC ($p < 0.050, r < -0.500, \text{see}\ \mathbf{Fig\ 2A - B}$). Moreover, PD-OFF needed more time to capture the dot in between the slides (i.e. a longer transition time) in both sliding tasks ($p < 0.050, r < -0.500, see\ \mathbf{Fig\ 2C - D}$). Accuracy of sliding performance did not

differ. Looking at the tapping task, neither the inter-tap interval time, nor tapping accuracy differed significantly between PD-OFF and HC. PD-OFF had higher VAS scores (i.e. more fatigue) for all tablet tasks compared to HC ($p < 0.050$, see **Table 2**).

Effect of medication

The comparison between medication conditions did not reveal significant effects for either sliding task. **Figure 2** and **Table 2** show that both the performance and transition times improved following medication intake with a large effect size, although not significantly. Similarly, the number of correctly performed sliding movements on the multi-direction sliding task worsened with a large effect size, though not significantly.

When comparing PD-ON with HC, no significant differences were found in the performance or transition time for the single sliding task ($\mathbf{Fig\ 2A - 2C}$). In the multi-direction sliding task, PD-ON had a significantly longer performance and transition time compared to HC ($p = 0.032, r = -0.530; p = 0.048, r = -0.507; resp.,$ **Fig 2B − 2D**). The error distance and the number of correctly performed sliding movements did not differ significantly on either sliding task.

Looking at the tapping task, medication led to a significant reduction in the inter-tap interval time ($p = 0.046, r = -0.657$). Despite the large effect size, medication conditions did not differ significantly in tapping accuracy. When compared to HC, PD-ON revealed a similar timing performance, although they were less accurate ($p = 0.028, r = -0.490$). Details are provided in **Table 2**. VAS values for all tablet tasks were similar between medication conditions ($p > 0.200$), yet PD-ON patients reported higher VAS scores than HC ($p < 0.100$), see **Table 2**.

Correlation analysis

A detailed overview of correlations between timing parameters of tablet tasks and general characteristics across groups (PD-OFF and HC) are displayed in **Table S1**. Looking at the association with daily life smartphone skills, longer performance and transition times of all tablet tasks were correlated with longer performance times on the MPT ($R > 0.400, p < 0.050, \mathbf{Fig.\ S1A - B}$), though not with the self-reported MDPQ-16 scores. A better manual dexterity, indicated by a lower score on the DEXTQ-24 ($R > 0.390, p < 0.060, \mathbf{Fig.\ S1C}$) and higher score on the Purdue Pegboard Test ($R < -0.350, p < 0.100$), was associated with faster performance on all tablet tasks.

In PD-OFF, a higher MDS-UPDRS-III score (i.e. worse disease severity) correlated with a longer inter-tap interval time, total sliding time on the single sliding task as well as transition time on the multi-direction sliding task ($R > 0.600, p < 0.050$). In contrast, patients with more severe right kinetic tremor (higher score on MDS-UPDRS-III item 16a) had faster total multi-direction sliding times ($R = -0.583, p = 0.047$). Lastly, higher HADS-scores (i.e. worse mental wellbeing) were significantly correlated with slower performance ($R > 0.450, p < 0.050$). No correlations were found with the other characteristics.

Daily smartphone skills

The questionnaires on daily smartphone use (**Table S2**) revealed that HC owning a smartphone (92%) did not report problems with smartphone use, whereas the majority of the smartphone owning patients (100%) did experience problems (92%). The most commonly reported problem was the small size of the icons and the keyboard (45%), followed by difficulties with tapping (27%). Also, difficulties with swiping (18%), double tapping (9%), button use (9%) and enlarging an image by swiping over the screen (9%), were indicated.

229 Interestingly, more PD patients mentioned to play games daily on the smartphone compared
230 to HC ($p = 0.047$).
231 **Table S3 provides** subscores of the MDPQ-16, assessing the ability to perform different tasks
232 on mobile devices**.** Lower scores indicate more difficulties, though the origin (motor or
233 cognitive) is not specified.[22] The total score did not differ significantly between groups ($p =$
234 0.221). However, PD patients experienced more difficulties with the performance of basic
235 skills (i.e. Mobile Device Basics), consisting of navigating through menus and using the
236 keyboard, compared to HC ($p = 0.019$). Also, searching and finding information on the
237 internet (i.e. Internet) and setting up passwords as well as deleting the search history (i.e.
238 Privacy) appeared to be more difficult for PD patients than for HC ($p < 0.050$). As for
239 performance on the MPT, PD patients were significantly slower in OFF than HC ($p =$
240 0.012, see $\mathbf{Fig.\ S2}$).

241 ## Discussion

242 This pilot study aimed to examine the effects of PD and dopaminergic medication on
243 touchscreen skills. We found a slower performance on most tablet tasks in PD-OFF compared
244 with HC, while accuracy did not differ between groups. After administration of dopaminergic
245 medication, performance times of the tapping and single sliding tasks improved to
246 comparable levels as HC. However, the complex multi-direction sliding movements remained
247 abnormal in PD.

248 **PD affects timing parameters**

249 We investigated if and why PD patients report difficulties with the motor aspects of
250 touchscreen manipulation and found that PD-OFF performed sliding movements more slowly
251 compared to HC in both single and multi-direction sliding tasks. These slower timing

252 parameters OFF medication partially support a lack of movement vigor or the presence of
253 bradykinesia in PD.[27] Here, we showed for the first time that this symptom also affects the
254 motor components of using a touchscreen device, particularly in the most difficult sliding task.
255 Also, slower transition times were found, i.e. patients needed more time to grab the dot after
256 terminating a sliding movement. Using a mobile device is not limited to actual movement
257 performance, but also requires transitioning towards the next movement, pointing towards
258 the complexity of touchscreen use. Although not recorded in the current study, the amount
259 of pressure exerted on the touchscreen may also influence transition performance.[28] As such,
260 daily use of touchscreen devices requires various complex skills, the exact coordination of
261 which needs further research.
262 As for accuracy measures, PD-OFF and HC did not differ in the number of correct sliding
263 movements. These different results for timing and accuracy parameters might be explained
264 by a difference in priority. PD-OFF might have moved more slowly towards the fixed targets
265 offered by the tablet tasks than HC, prioritizing accuracy over movement time.[29]
266 Regarding the tapping task, we found no significant differences in inter-tap interval time
267 between PD-OFF and HC, as opposed to the results of Wissel et al.[11] Patients in this latter
268 study had worse disease severity compared to our study sample, suggesting that disease
269 severity may be related to tapping performance. Our findings of a significant correlation
270 between MDS-UPDRS-III score and inter-tap interval time further support this. The differing
271 findings also need to be interpreted against the correction for multiple testing applied in our
272 study. Contrary to the timing, tapping accuracy was similar between groups in both studies.[11]
273 Overall, the results of the tapping task further support the importance of comprehensive test
274 batteries containing multiple tasks to identify specific problems with touchscreen use in PD.

275 **Impact of clinical characteristics**

276 Generally, tapping, sliding and transition times correlated positively with the more functional
277 MPT and DEXTQ-24 scores, indicating the relevance of the tasks for capturing the capacity of
278 touchscreen manipulation. Together with the negative correlations with the Purdue Pegboard
279 Test, it confirms that dexterous deficits affect touchscreen usage in PD, even more so when
280 patients are OFF medication.[5] Correlations with MDS-UPDRS-III scores were found, indicating
281 that patients with worse disease severity have a worse tablet task performance. Moreover, a
282 worse right upper limb kinetic tremor was associated with a faster total multi-direction sliding
283 time. This is an intriguing result as we expected a correlation in the opposite direction, but
284 tremor did not otherwise impact the findings. Apart from the stronger correlations with
285 motor capacity, we also demonstrated an association between timing parameters and
286 measures for mental wellbeing mainly for PD-OFF, suggesting that the presence of depression
287 may have affected the motivation for touchscreen performance. The high cognitive scores in
288 the current study might explain the lack of significant correlations with executive function
289 (TMT performance) and cognitive function in general. Therefore, future studies should
290 consider participants with a broad spectrum of cognitive impairments to clarify the impact of
291 cognitive function on touchscreen manipulation.[30]

292 **Partial effects of dopaminergic medication**

293 Medication improved performance times of the tapping and single sliding tasks to the level
294 of HC, corroborating the known dopaminergic effects on bradykinetic symptoms and on
295 tapping performance.[11] According to a recent review, dopaminergic medication increases the
296 activity in the cortico-subcortical network related to the invigoration of movements.[8] In
297 contrast, transition times did not differ between medication conditions in both sliding tasks.

298 It is likely that transition times reflected the ability to chunk motor components as it consisted
299 of stopping the sliding movement, transitioning towards the dot, grabbing the dot and then
300 starting the sliding movement again. One can thus expect that transition times capture not
301 only motor function but also cognitive flexibility, suggesting that both motor and cognitive
302 aspects were involved in the relatively simple touchscreen manipulations tested in this study.
303 The discrepancy in medication effects on these timing parameters also underscores the need
304 for the design of novel training interventions that target the varied aspects of touchscreen
305 skills.

306 Looking at accuracy, no significant effects of anti-parkinsonian medication were found for
307 both sliding tasks. Tapping accuracy, on the contrary, was worse in PD-ON compared to HC.
308 This is in line with previous work showing that medication had a deleterious effect on
309 movement accuracy, while improving movement time.[11]

310 Overall, these findings imply that dopaminergic medication has a positive effect on the
311 simpler aspects of touchscreen motions as opposed to the more complex sliding tasks. These
312 results underscore that simple, repetitive tasks, underestimate the problems with
313 touchscreen manipulation in PD. Although simple assessments are most frequently used,
314 future research should include more comprehensive test batteries revealing the complex
315 reality of touchscreen use.

316 Medication administration resulted in similar performance levels as HC, as differences in the
317 single sliding task and in inter-tap interval time between patients and HC were no longer
318 significant. This is an important finding as it can be assumed that most patients use their
319 mobile devices while ON medication in daily life. However, medication did not ameliorate all
320 aspects. These partial effects of dopaminergic medication could also explain the many self-

321 reported difficulties with using mobile devices by patients, probably further exacerbated by
322 the distraction experienced in daily life.

323 **Clinical implications and future research**

324 Previous research showed that patients who experienced more difficulties with technology,
325 might dropout of studies using smartphone interventions.[31] This suggests the need for specific
326 training programs to address these problems, making sure that transfer is addressed to daily
327 life. Such interventions could be delivered in the home setting, shown to be successful for
328 improving dexterity[32] as well as micrographia in PD.[33] Furthermore, we recently
329 demonstrated benefits of short-term learning of unlocking a touchscreen trace.[7] Importantly,
330 all these training programs proved feasible without much supervision yet high adherence,[34]
331 suggesting a cost-effective approach for tackling touchscreen deficiencies in the future.
332 The slower performance on the tablet tasks together with the self-reported difficulties
333 experienced by PD patients, suggest the need for thoughtful development of smartphone
334 applications for patients. Considering the more pronounced problems with the complex
335 aspects of tablet tasks, more simple handling of E-health applications should be provided, e.g.
336 by avoiding multidirectional movements or double tapping. Nunes et al.[5] provided
337 preliminary guidelines for such developments, needing further validation.

338 **Study limitations**

339 Several limitations should be considered when interpreting our findings. First, the small
340 sample size may have increased the risk of type II errors, which may have underestimated the
341 medication effects on movement accuracy. We used the Bonferroni method to correct for
342 multiple testing, ensuring an overall conservative approach to our statistical analysis. The
343 small sample size also prevents generalization to the broader PD population. Additionally, we

focused on the motor aspects of touchscreen use supporting the need for future research implementing additional cognitive load. The ON tests were performed after the OFF tests possibly resulting in order effects, although we did not find differences in VAS scores for fatigue. In addition, and despite some familiarization after trial 1, we showed acceptable reliability of repeated trials.

Conclusion

Overall, we found that PD patients had poorer touchscreen skills compared to age-matched healthy controls, especially when performing multi-direction sliding movements and when capturing a target. Some of the milder difficulties were alleviated with dopaminergic treatment, but the more complex tasks remained below the levels of healthy controls. These findings underscore the message that efficient utilization of mobile devices should not be assumed in PD. Therefore, future research is needed to investigate the developments of E-health applications and novel neurorehabilitation programs, which are tailor-made to ensure that people with PD can partake optimally in society.

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Author roles

1. Research project: A. Conception, B. Organization, C. Execution; 2. Statistical analyses: A. Design; B. Execution, C. Review and Critique; 3. Manuscript preparation: A. Writing of the first draft, B. Review and Critique.

366 JDV: 1C, 2A, 2B, 3A

367 SB: 2C, 3B

368 LJ: 1A, 3B

369 EH: 1A, 3B

370 AN: 1A, 2C, 3B

371 EN: 1A, 1B, 1C, 2A, 2C, 3A, 3C

372 Disclosures

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381 Ethical Compliance Statement

382 This study was approved by the local Ethics committee UZ/KU Leuven according to the code
383 of Ethics of the World Medical Association (Declaration of Helsinki, version 2013, S61793).
384 Prior to participation in the study, an informed consent form was signed after explanation of
385 the study protocol. We confirm that we have read the Journal's position on issues involved in
386 ethical publication and affirm that this work is consistent with those guidelines.

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487

Figure Legends

Figure 1. Tablet tasks. Tapping between two dots (left panel). Sliding a dot towards a predefined target in a single direction (middle panel). Sliding a dot towards a predefined target in multiple directions (right panel).

Figure 2. Performance on tablet tasks. **A.** Total single direction sliding time (ms). **B.** Total multi-direction sliding time (ms). **C.** Transition time (ms) on the Single Sliding task. **D.** Transition time (ms) on the Multi-direction Sliding task.

Legends of Supplemental files

Supplementary Material S1. Repeatability analysis

Supplementary Table S1. Correlation analysis across groups and in both groups separately.

Supplementary Table S2. Smartphone specific questions. Descriptive use of mobile devices

Supplementary Table S3. Mobile Device Proficiency Questionnaire (MDPQ-16)

Supplementary Figure S1. Correlations between performance on tablet tasks and clinical characteristics across groups (PD-OFF and HC). **A.** Total sliding time (ms) on the Single sliding task and MPT performance (s). **B.** Transition time (ms) on the Multi-direction sliding task with MPT performance (s). **C.** Transition time on the Multi-direction sliding task with scores on the dexterity questionnaire (DEXTQ-24). Filled circles = PD-OFF patients; unfilled circles = healthy controls.

Supplementary Figure S2. Comparison performance on mobile phone task (MPT) between groups. Mann-Whitney U test compared patients with healthy controls. differences are

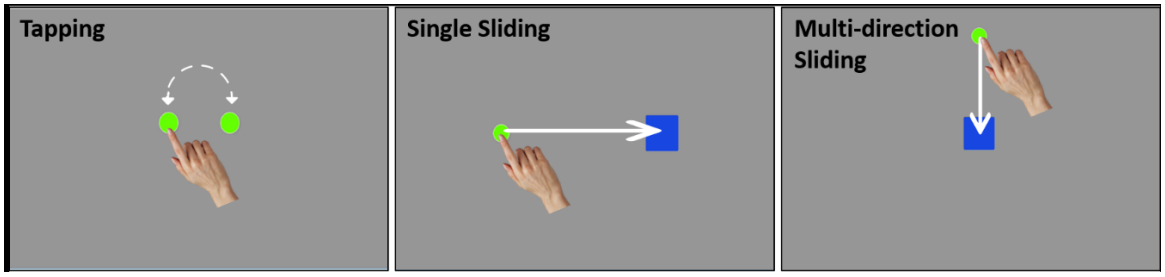
508 indicated by square brackets. Wilcoxon Signed Ranks test compared medication conditions.

509 * Group differences at P < 0.050; # Group differences at P < 0.100.

510 **Supplementary Appendix.** Smartphone specific questions (translated to English)

511

512 **Figures**

513 

514 **Figure 1. Tablet tasks**. Tapping between two dots (left panel). Sliding a dot towards a
515 predefined target in a single direction (middle panel). Sliding a dot towards a predefined
516 target in multiple directions (right panel).

517

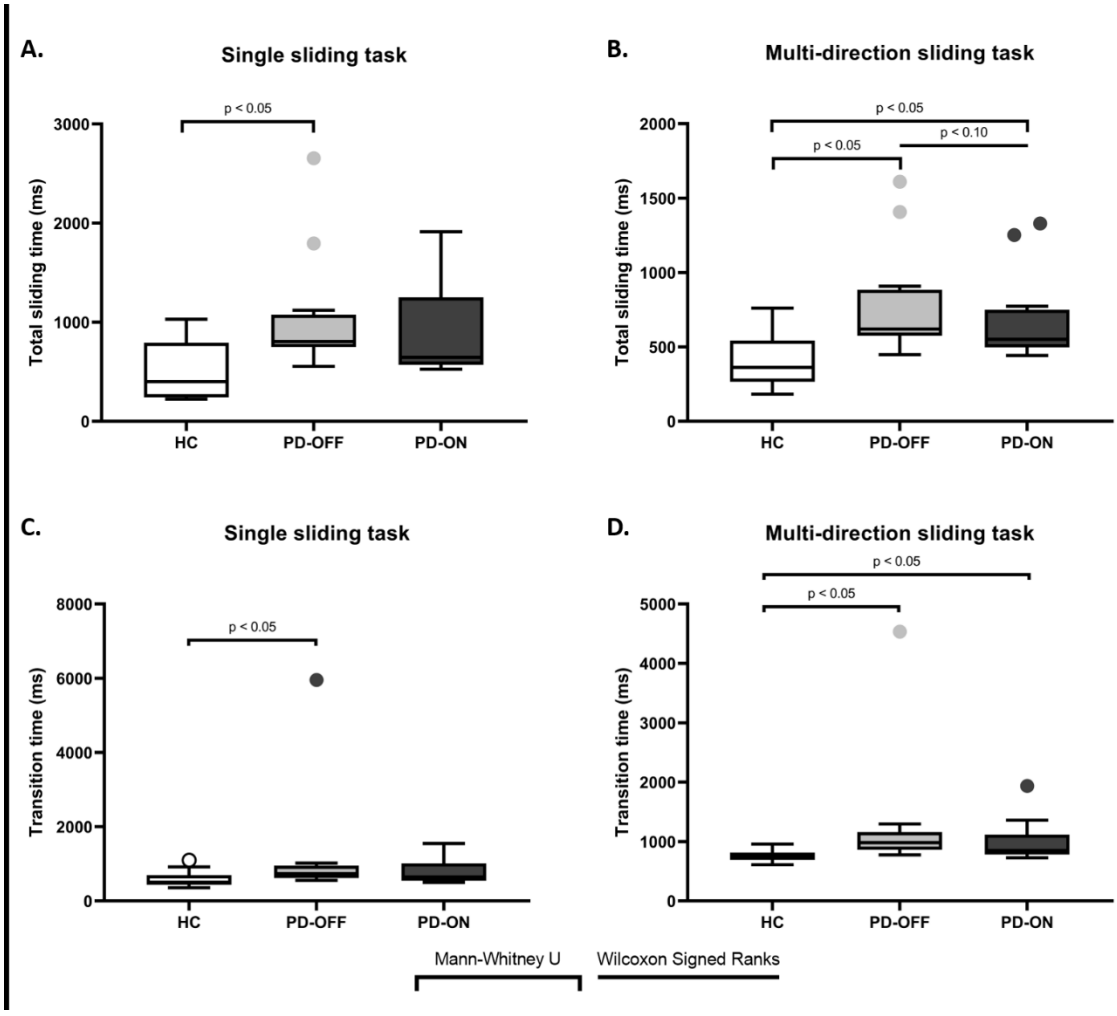


Figure 2. Performance on tablet tasks. **A.** Total single direction sliding time (ms). **B.** Total multi-direction sliding time (ms). **C.** Transition time (ms) on the Single Sliding task. **D.** Transition time (ms) on the Multi-direction Sliding task.

522 # Tables

Table 1.
Clinical characteristics and demographics for all participants

	PD patients (N = 12)		HC (N = 12)	P-value (PD vs HC)	P-value (OFF vs ON)
	PD-OFF	PD-ON			
Age (years)	64.7 (6.7)		68.7 (6.9)	0.160	
Gender (M/F)	9/3		8/4	0.653	
EHI (%)	95 (90; 100)		100 (100; 100)	0.198	
MMSE (0-30)	29.5 (26.8; 30)		29 (28.8; 30)	0.799	
MoCA (0-30)	27.3 (1.9)		25.6 (2.8)	0.084	
TMT (B-A) (s)	45.5 (29.1)		37.9 (19.0)	0.455	
HADS-Anxiety (0-21)	7.6 (4.4)		4.7 (3.0)	0.073	
HADS-Depression (0-21)	6.8 (3.7)		2.8 (1.7)	0.002*	
DEXTQ-24	33 (27.8; 35.5)		24 (24; 24)	< 0.001*	
PPT-R (#pegs/30s)	9 (7; 11)	11 (8.8; 11)	13 (12.8; 13)	< 0.001*	0.064
PPT-L (#pegs/30s)	8.6 (2.2)	9 (2.1)	10.8 (1.6)	0.009*	0.496
PPT-RL (#pegs/30s)	12.9 (5.0)	12.82 (4.1)	19.1 (3.0)	0.003*	0.852
PPT-Combi (#parts/ min)	14 (12.5; 17.5)	19 (13; 22)	21.5 (21; 25.3)	0.001*	0.089
NFOG-Q (0-28)	4 (0; 10.8)		-		
H&Y (II/III)	8/3	9/2	-		1.000
MDS-UPDRS-III (0-132)	36 (32; 43.5)	26 (24.5; 30.5)	-		0.003*
MDS-UPDRS-III-UL (0-60)	19 (17; 23)	12 (11; 16)	-		0.003*
MDS-UPDRS-III item 15a (0-4)	1 (0.8; 1)	1 (0; 0)	-		0.317
MDS-UPDRS-III item 16a (0-4)	1 (1; 1)	1 (1; 1)	-		0.046*
MDS-UPDRS-III item 17a (0-4)	0 (0; 1)	0 (0; 0)	-		0.102
LEDD (mg/24h)	867.1 (290.1)		-		
Disease Duration (years)	10.6 (3.9)		-		

Abbreviations: PD = Parkinson's disease; HC = healthy controls; OFF = OFF medication; ON = ON medication; EHI = Edinburgh Handedness Inventory; item 15a = postural tremor, right hand; item 16a = kinetic tremor, right hand; item 17a = rest tremor amplitude, right upper extremity; MMSE = Mini Mental State Examination; MoCA = Montreal Cognitive Assessment; TMT = Trail making test; HADS = Hospital Anxiety and Depression Scale; DEXTQ = Dexterity questionnaire; PPT = Purdue Pegboard Test; R = right; L = left; RL = Bimanual; Combi = combination; H&Y = Hoehn and Yahr; MDS-UPDRS-III = Movement Disorders Society – Unified Parkinson's Disease Rating Scale part 3; UL = upper limb; LEDD = L-dopa equivalent daily dosage; # = number of
Normally distributed variables are displayed as the mean (standard deviation). Non-normally distributed variables are presented as the median (1st quartile; 3rd quartile). * Group significant different at P < 0.050.

523

Table 2.
Comparison of performance on touchscreen skills between PD patients and healthy controls.

	HC (N = 12)	PD-OFF (N = 12)	PD-ON (N = 12)	OFF vs HC		OFF vs ON		ON vs HC	
				P-value	r	P-value	r	P-value	r
Slide Single									
Total time (ms)	400.7 (257.6; 771.7)	805.6 (752.2; 985.2)	645.0 (601.4; 935.6)	0.048*	-0.507	0.164	-0.589	0.272	-0.377
Transition time (ms)	503.4 (463.9; 684.1)	736.7 (641.6; 928.1)	645.1 (546.7; 984.1)	0.040*	-0.518	1.388	-0.272	0.133	-0.436
Error (pixels)	31.9 (19.1; 46.8)	18.8 (13.7; 25.1)	18.0 (16.5; 25.6)	0.404	-0.342	4.000	0.000	0.312	-0.365
Accuracy (%)	91.1 (81.7; 94.4)	89.4 (80.8; 96.7)	90.6 (81.1; 96.1)	3.372	-0.041	3.156	-0.077	3.020	-0.065
Slide Multi									
Total time (ms)	362.6 (276.2; 497.2)	620.5 (583.5; 836.5)	551.7 (513.1; 701.7)	0.004*	-0.625	0.076	-0.679	0.032*	-0.530
Transition time (ms)	754.1 (698.0; 812.3)	982.2 (868.5; 1100.9)	847.4 (803.7; 1112.1)	< 0.001*	-0.707	0.468	-0.453	0.048*	-0.507
Error (pixels)	25.0 (20.6; 36.4)	19.7 (17.7; 23.7)	20.5 (19.0; 22.7)	0.312	-0.037	1.232	-0.294	0.512	-0.318
Accuracy (%)	83.9 (80.5; 89.8)	85.4 (75.0; 89.3)	79.2 (71.1; 89.3)	3.728	-0.024	0.240	-0.544	1.388	0.195
Tap									
Time (ms)	263.5 (196.4; 310.2)	332.1 (239.0; 459.4)	277.85 (218.0; 369.4)	0.120	-0.389	0.046*	-0.657	0.638	-0.212
Accuracy (%)	92.8 (89.7; 95)	88.9 (79.7; 97.7)	78.3 (67.8; 85)	1.686	-0.041	0.130	-0.533	0.028*	-0.490
VAS score									
Tap	0.8 (0.3; 1.0)	1.5 (0.8; 1.9)	1.4 (1; 1.7)	0.024*	-	0.759	-	0.033*	-
Slide Single	0.7 (0.3; 1.3)	1.95 (1.6; 2.75)	1.9 (1.2; 2.6)	0.014*	-	0.432	-	0.052	-
Slide Multi	0.9 (0.3; 1.5)	2.4 (1.9; 4)	2.3 (1.5; 3.3)	0.014*	-	0.255	-	0.033*	-

Data are presented as the median (1st quartile; 3rd quartile). Mann-Whitney U tests compared performance of PD patients with HC. Wilcoxon signed ranks tests compared PD patients OFF and ON medication.

* Group significant different at P < 0.050.

Abbreviations: PD = Parkinson's disease; OFF = OFF medication; HC = healthy controls; ON = ON medication; VAS = Visual Analogue Scale; r = effect size estimate

Supplementary material. Repeatability analysis

An additional analysis was performed to explore the repeatability between the different trials performed by the participants. First, we used Bland-Altman plots to assess the repeatability between the first fifteen repetitions and the last fifteen repetitions of trial 1. The plots provided in **Figure 1** revealed a good repeatability. Second, we explored the repeatability between trial 1 and 3 using Bland-Altman plots (**Figure 2**). Although most parameters had a good repeatability between the first and the last trial, some did not. Therefore, Friedman tests were performed to compare all three trials, with Wilcoxon signed-rank tests as post-hoc analyses (with a Bonferroni correction). Results for PD-OFF+HC and PD-ON+HC are provided in **Table 1 – 2**. In line with the Bland-Altman plots, results showed that the differences were mainly situated between trial 1 and 3 and between trial 1 and 2, though not between trial 2 and 3, with the exception of one parameter (i.e. transition time of the Single Sliding task). These results were indicative of a mild degree of learning between the first and third trial. Hence, we conducted a sensitivity analysis only using trial 2 and 3 revealing that our initial results, including the pooled data of the three trials, remained (**Table 3**).

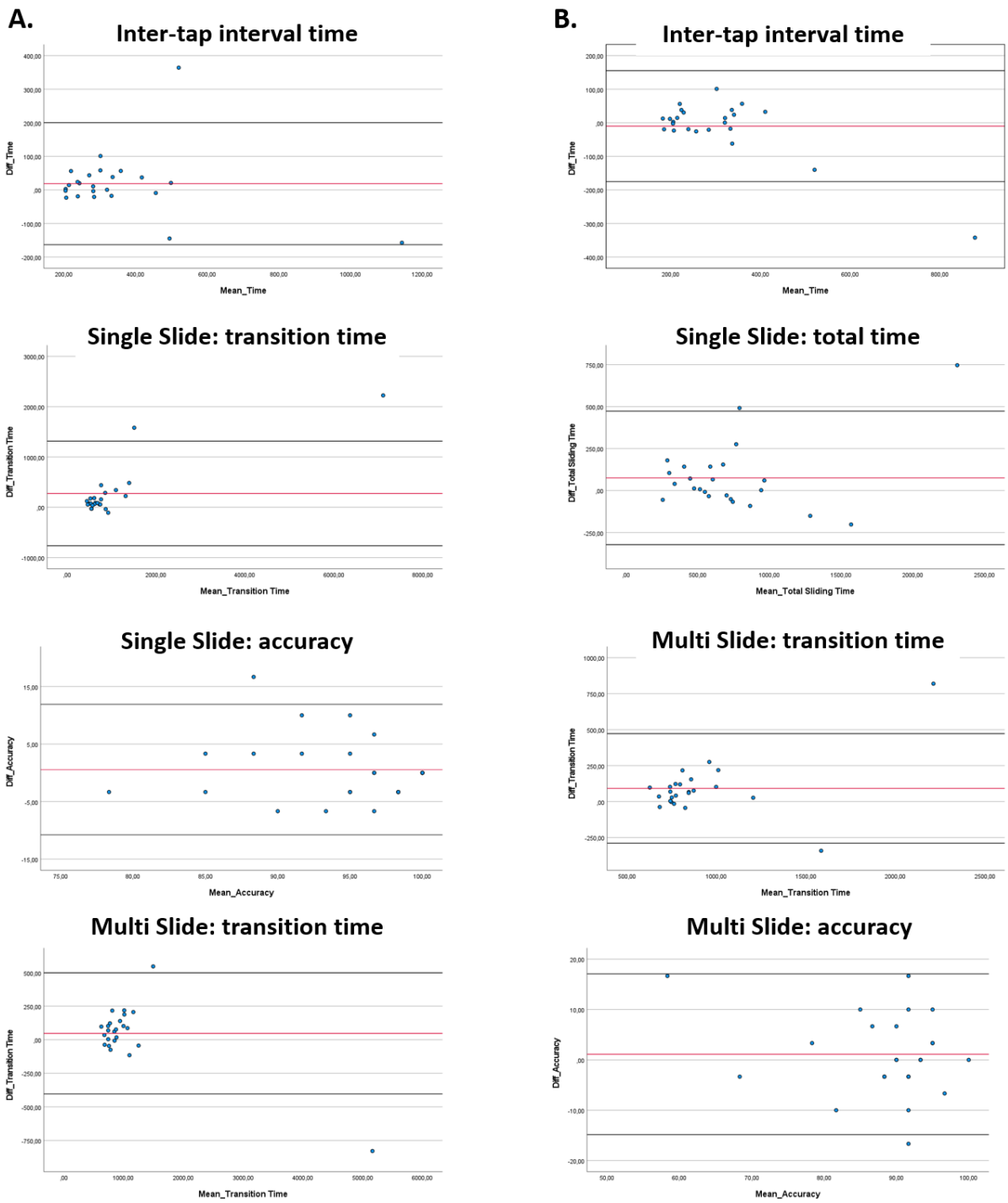


Figure 1. Bland-Altman plots showing the repeatability between the first fifteen repetitions and the last fifteen repetitions of trial 1. **A.** Data from PD-OFF patients and HC. **B.** Data from PD-ON patients and HC.

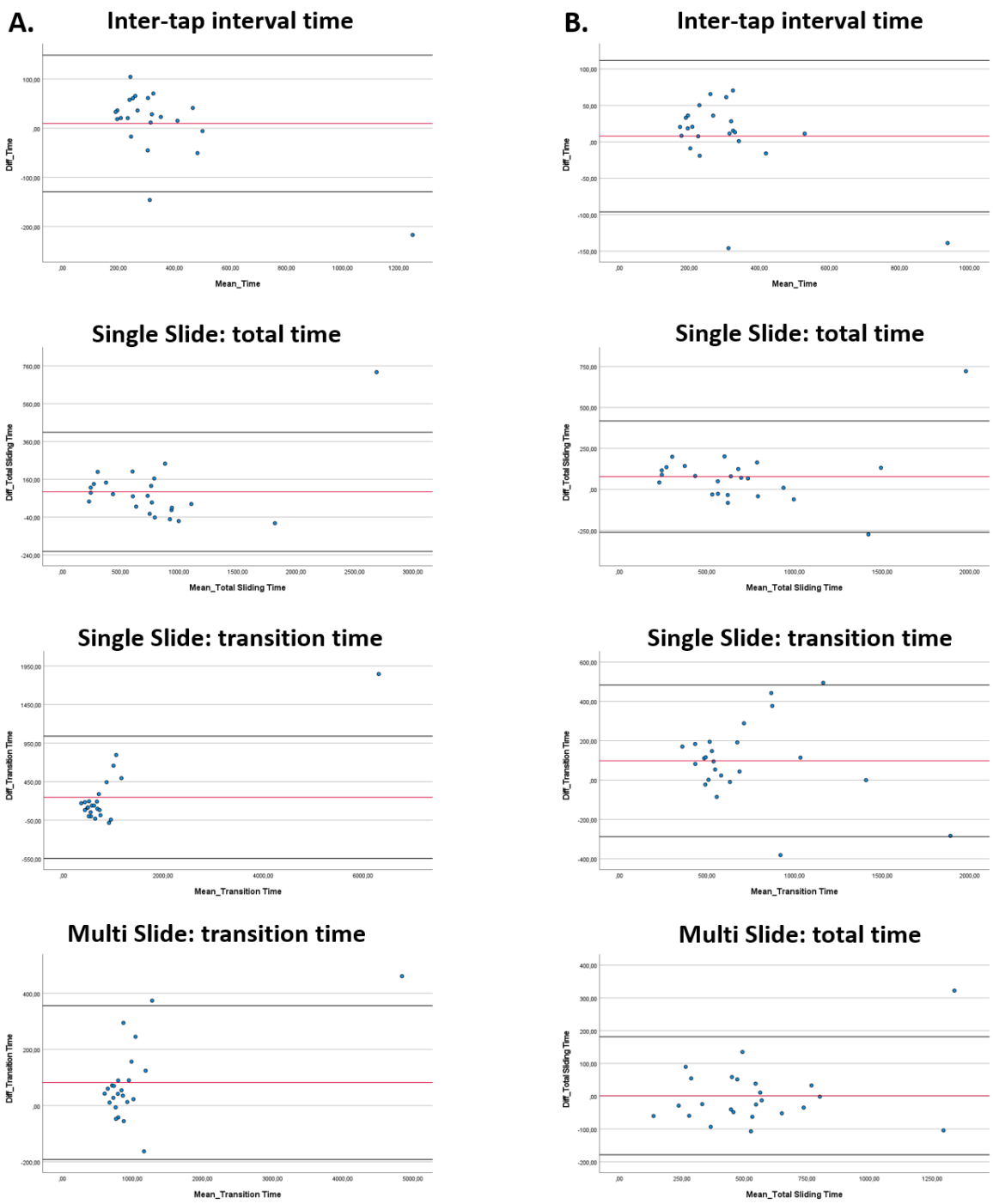


Figure 2. Bland-Altman plots showing the repeatability between the first trial and the last trial. **A.** Data from PD-OFF patients and HC. **B.** Data from PD-ON patients and HC.

Table 1. Friedman tests assessing differences between the three trials of each tablet task for all parameters, for performance of PD-OFF patients and HC. Post-hoc analyses were conducted with Wilcoxon signed-rank tests with a Bonferroni correction.

	Chi-square value OR Z-value	**p-value**
Tap Time	**6.348**	**0.042***
Trial 1 vs 2	Z = -2.057	0.120
Trial 2 vs 3	Z = -0.517	1.815
Trial 1 vs 3	Z = -1.794	0.219
Tap Accuracy	**0.575**	**0.750**
S1 Total Sliding Time	**11.083**	**0.004***
Trial 1 vs 2	Z = -2.771	0.018
Trial 2 vs 3	Z = -1.714	0.258
Trial 1 vs 3	Z = -3.057	0.006*
S1 Transition Time	**21.583**	**< 0.001***
Trial 1 vs 2	Z = -3.714	< 0.001*
Trial 2 vs 3	Z = -2.771	0.018*
Trial 1 vs 3	Z = -3.743	< 0.001*
S1 Error distance	**1.083**	**0.582**
S1 Accuracy	**0.078**	**0.962**
S2 Total Sliding Time	**2.583**	**0.275**
S2 Transition Time	**12.583**	**0.002***
Trial 1 vs 2	Z = -3.057	0.006
Trial 2 vs 3	Z = -0.914	1.083
Trial 1 vs 3	Z = -2.829	0.015
S2 Error distance	**7.583**	**0.023***
Trial 1 vs 2	Z = -2.971	0.009
Trial 2 vs 3	Z = -1.314	0.567
Trial 1 vs 3	Z = -1.514	0.390
S2 Accuracy	**0.179**	**0.914**

Abbreviations: PD-OFF = PD-patients without medication; HC = healthy controls; S1 = Single Sliding task; S2 = Multi-direction Sliding task

Table 2. Friedman tests assessing differences between the three trials of each tablet task for all parameters, for performance of PD-ON patients and HC. Post-hoc analyses were conducted with Wilcoxon signed-rank tests with a Bonferroni correction.

	Chi-square value OR Z-value	**p-value**
Tap Time	**8.769**	**0.012***
Trial 1 vs 2	Z = -1.460	0.342
Trial 2 vs 3	Z = -0.973	0.990
Trial 1 vs 3	Z = -2.099	0.108
Tap Accuracy	**0.947**	**0.623**
S1 Total Sliding Time	**8.583**	**0.014***
Trial 1 vs 2	Z = -1.800	0.216
Trial 2 vs 3	Z = -1.800	0.216
Trial 1 vs 3	Z = -2.629	0.027*
S1 Transition Time	**15.250**	**< 0.001***
Trial 1 vs 2	Z = -2.743	0.018*
Trial 2 vs 3	Z = -2.143	0.096
Trial 1 vs 3	Z = -2.657	0.024*
S1 Error distance	**0.583**	**0.747**
S1 Accuracy	**0.683**	**0.711**
S2 Total Sliding Time	**1.750**	**0.417**
S2 Transition Time	**7.583**	**0.023***
Trial 1 vs 2	Z = -1.171	0.723
Trial 2 vs 3	Z = -1.429	0.459
Trial 1 vs 3	Z = -2.086	0.111
S2 Error distance	**1.083**	**0.582**
S2 Accuracy	**1.767**	**0.413**

Abbreviations: PD-ON = PD-patients with medication; HC = healthy controls; S1 = Single Sliding task; S2 = Multi-direction Sliding task

Table 3. Sensitivity analysis. Comparison of performance on touchscreen skills between PD patients and healthy controls, considering the pooled data of only trial 2 and 3.

	HC (N = 12)	PD-OFF (N = 12)	PD-ON (N = 12)	OFF vs HC		OFF vs ON		ON vs HC	
				P-value	r	P-value	r	P-value	r
Slide Single									
Total time (ms)	371.01 (228.6; 760.1)	760.98 (739.5; 1002.5)	637.47 (578.9; 955.0)	0.048*	-0.507	0.240	-0.544	0. 180	-0.413
Transition time (ms)	495.76 (422.2; 624.6)	725.15 (637.3; 816.6)	633.88 (554.2; 975.9)	0.032*	-0.530	2.332	-0.158	0.112	-0.448
Error (pixels)	29.28 (19.9; 45.7)	19.16 (12.1; 27.2)	18.47 (17.0; 23.9)	0.404	-0.342	3.500	-0.045	0.180	-0.413
Accuracy (%)	93.33 (84.2; 95.4)	88.33 (81.3; 98.8)	90.00 (79.6; 95.8)	3.372	-0.041	2.300	-0.162	3.908	-0.012
Slide Multi									
Total time (ms)	379.26 (257.4; 464.9)	617.84 (556.9; 793.8)	569.01 (518.4; 728.8)	0.004*	-0.625	0.164	-0.589	0.020*	-0.566
Transition time (ms)	736.11 (688.5; 786.1)	950.66 (857.5; 1088.8)	859.23 (816.4; 921.8)	< 0.001*	-0.731	0.336	-0.498	0.024*	-0.554
Error (pixels)	25.67 (20.5; 35.2)	18.17 (16.2; 21.8)	20.74 (19.4; 22.3)	0.096	-0.460	0.544	-0.430	0.404	-0.342
Accuracy (%)	83.59 (78.5; 92.6)	83.59 (77.7; 92.2)	82.03 (71.5; 91.4)	3.196	-0.053	0.892	-0.352	2.056	-0.142
Tap									
Time (ms)	250.41 (191.4; 304.2)	337.04 (233.7; 450.0)	279.89 (209.3; 374.5)	0.066	-0.436	0.082	-0.589	0.582	-0.224
Accuracy (%)	92.50 (87.9; 95.4)	85.00 (72.5; 97.1)	75.00 (71.7; 85.4)	1.426	-0.083	0.846	-0.232	0.066	-0.432

Data are presented as the median (1st quartile; 3rd quartile). Mann-Whitney U tests compared performance of PD patients with HC. Wilcoxon signed ranks tests compared PD patients OFF and ON medication.
* Group significant different at P < 0.050.
Abbreviations: PD = Parkinson's disease; OFF = OFF medication; HC = healthy controls; ON = ON medication

Supplementary Tables

Supplementary table 1. Correlation analysis across groups and in both groups separately.

		Inter-tap interval time		S1: total time		S1: transition time		S2: total time		S2: transition time	
		R	P-value	R	P-value	R	P-value	R	P-value	R	P-value
Age	All	0.147	0.494	0.106	0.621	0.040	0.854	-0.118	0.584	0.009	0.966
Daily life smartphone skills											
MPT (s)	All	0.551	**0.005***	0.596	**0.002***	0.498	**0.013***	0.513	**0.010***	0.725	**< 0.001***
	PD-OFF	0.487	0.108	0.683	**0.014***	0.420	0.174	0.673	**0.017***	0.666	**0.018***
	HC	0.524	0.080	0.371	0.236	0.273	0.391	0.028	0.931	0.490	0.106
MDPQ-16	All	-0.281	0.183	-0.276	0.192	-0.390	0.059	-0.305	0.147	-0.276	0.192
	PD-OFF	-0.495	0.102	-0.053	0.871	-0.053	0.871	-0.088	0.786	-0.074	0.820
	HC	0.049	0.879	-0.333	0.290	-0.614	**0.034***	-0.239	0.455	-0.204	0.526
Motor function											
DEXTQ-24	All	0.393	0.058	0.473	**0.019***	0.467	**0.022***	0.615	**0.001***	0.688	**< 0.001***
	PD-OFF	0.250	0.432	0.201	0.531	0.233	0.466	0.536	0.072	0.303	0.338
	HC	0.259	0.416	-0.065	0.841	-0.194	0.545	-0.259	0.416	0.000	1.000
PPT-R	All	-0.499	**0.013***	-0.482	**0.017***	-0.452	**0.027***	-0.556	**0.005***	-0.711	**< 0.001***
	PD-OFF	-0.276	0.386	-0.527	0.079	-0.410	0.186	-0.721	**0.008***	-0.629	**0.028***
	HC	-0.707	**0.010***	0.012	0.971	0.207	0.518	0.141	0.663	-0.180	0.576
PPT-RL	All	-0.553	**0.006***	-0.564	**0.005***	-0.445	**0.033***	-0.465	**0.025***	-0.699	**< 0.001***
	PD-OFF	-0.496	0.121	-0.851	**0.001***	-0.664	**0.026***	-0.617	**0.043***	-0.711	**0.014***
	HC	-0.364	0.244	0.093	0.774	0.361	0.249	0.325	0.303	-0.014	0.965
PPT-COMBI	All	-0.518	**0.011***	-0.572	**0.004***	-0.457	**0.028***	-0.519	**0.011***	-0.726	**< 0.001***
	PD-OFF	-0.215	0.525	-0.719	**0.013***	-0.467	0.148	-0.636	**0.035***	-0.746	**0.008***
	HC	-0.580	**0.048***	-0.057	0.860	0.203	0.527	0.228	0.476	-0.061	0.852
MDS-UPDRS-III	PD-OFF	0.636	**0.035***	0.627	**0.039***	0.436	0.180	0.491	0.125	0.636	**0.035***

MDS-UPDRS-III item 15a	PD-OFF	0.347	0.269	-0.225	0.483	0.039	0.903	-0.067	0.836	-0.146	0.651
MDS-UPDRS-III-item 16a	PD-OFF	-0.130	0.688	-0.518	0.084	-0.194	0.545	-0.583	**0.047***	-0.389	0.212
MDS-UPDRS-III item 17a	PD-OFF	0.532	0.075	0.118	0.714	0.138	0.669	0.079	0.808	0.256	0.421
Cognitive function and mental wellbeing											
MoCA	All	-0.195	0.362	-0.086	0.690	0.014	0.946	0.065	0.763	-0.015	0.945
TMT (B-A) (s)	All	0.108	0.616	0.282	0.182	0.200	0.349	0.223	0.294	0.307	0.145
HADS-Anxiety	All	0.487	**0.016***	0.333	0.112	0.459	**0.024***	0.304	0.148	0.446	**0.029***
	PD-OFF	0.768	**0.004***	0.810	**0.001***	0.831	**0.001***	0.697	**0.012***	0.782	**0.003***
	HC	0.127	0.694	-0.389	0.212	-0.011	0.974	-0.286	0.367	-0.099	0.760
HADS-Depression	All	0.314	0.135	0.567	**0.004***	0.467	**0.021***	0.563	**0.004***	0.592	**0.002***
	PD-OFF	0.311	0.325	0.774	**0.003***	0.629	**0.028***	0.721	**0.008***	0.636	**0.026***
	HC	0.072	0.824	-0.018	0.956	0.014	0.965	-0.241	0.451	0.119	0.714

Significant correlation at * $P < 0.050$.

Abbreviations: PD-OFF = Parkinson's disease while OFF medication; HC = healthy controls; DEXTQ-24 = Dexterity questionnaire; HADS = Hospital Anxiety and Depression Scale; MDPQ-16 = Mobile device proficiency questionnaire; MDS-UPDRS-III = Movement Disorders Society Unified Parkinson's disease Rating Scale part III; MoCA = Montreal Cognitive Assessment; MPT = mobile phone task; PPT = Purdue Pegboard Test; R = right; RL = Bimanual; Combi = combination; S1 = Slide Single task; S2 = Slide Multi task; TMT = Trail Making test

Supplementary table 2. Smartphone specific questions. Descriptive use of mobile devices

	PD patients (N = 12)	HC (N = 12)	P-value
Smartphone	12 / 12 (100%)	11 / 12 (92%)	0.307
Daily games	5 / 12 (42%)	2 / 11 (18%)	0.047*
Use of smartphone			
Texting and calling	12 / 12 (100%)	11 / 11 (100%)	1.000
Internet use	11 / 12 (92%)	11 / 11 (100%)	0.328
Games (not daily)	8 / 12 (67%)	6 / 11 (55%)	0.552
All of the above	6 / 12 (50%)	6 / 11 (55%)	0.827
Difficulties with smartphone use	11 / 12 (92%)	0 / 11 (0%)	< 0.001*
Tapping	3 / 11 (27%)	-	
Double tapping	1 / 11 (9%)	-	
Swiping	2 / 11 (18%)	-	
Size of icons	5 / 11 (45%)	-	
Other	6 / 11 (55%)	-	

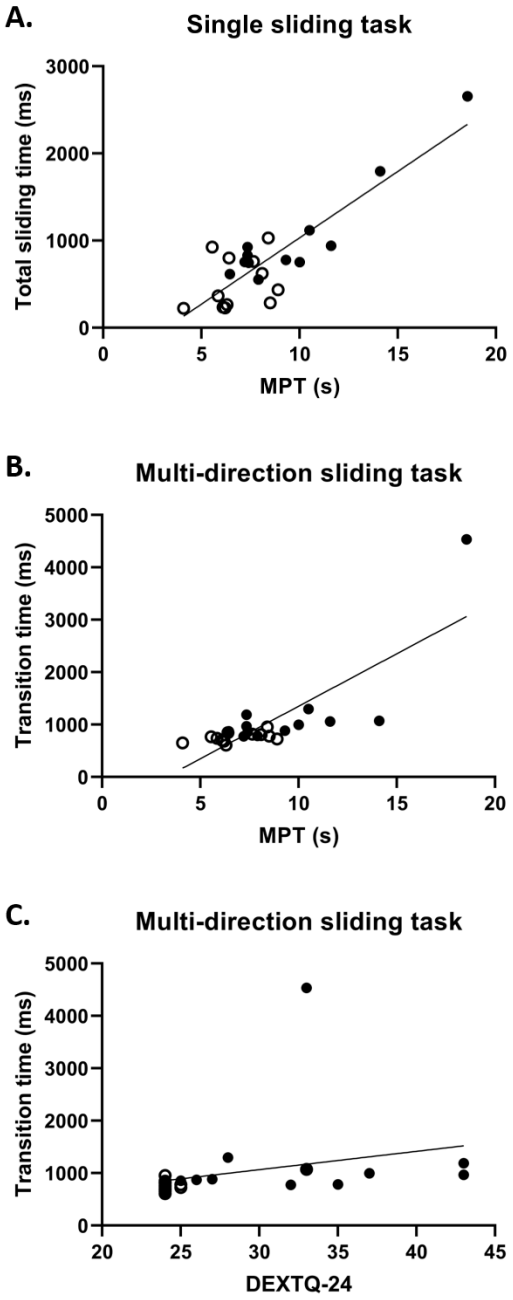
Abbreviations: PD = Parkinson's disease; HC = healthy controls
Data are presented as observed / total (percentage). * Group significant different at P < 0.050.

Supplementary table 3. Mobile Device Proficiency Questionnaire (MDPQ-16)

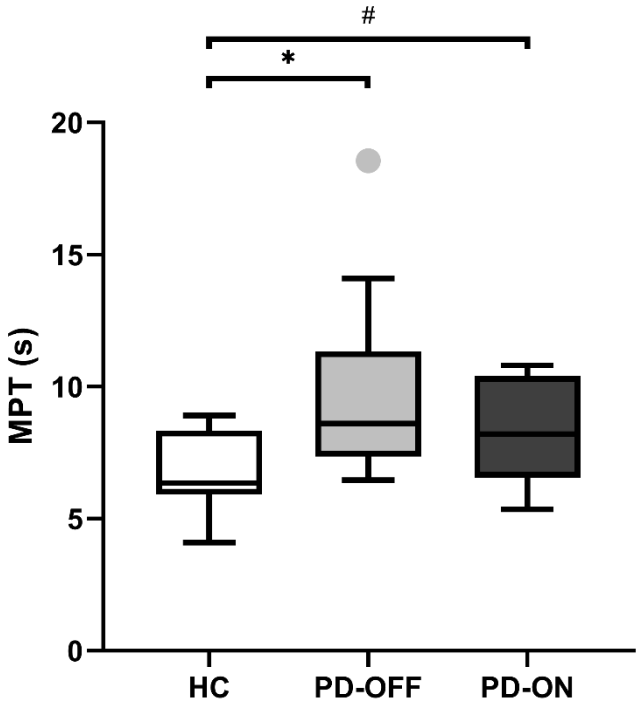
	PD patients (N = 12)	HC (N = 11)	P-value
1. Mobile Device Basics	7 (7; 10)	9 (8.75; 10)	0.019*
2. Communication	7 (2; 10)	9.5 (7.5; 10)	0.118
3. Data and File Storage	3 (2; 5.25)	3.5 (2; 5.25)	0.833
4. Internet	6 (5.75; 10)	10 (7.5; 10)	0.023*
5. Calendar	8 (2; 10)	5.5 (2; 10)	0.928
6. Entertainment	6 (4.75; 6)	6 (2; 6)	0.833
7. Privacy	7 (5; 10)	10 (7.5; 10)	0.044*
8. Troubleshooting and Software Management	9 (4.5; 10)	6 (2; 10)	0.740
TOTAL SCORE	51 (44; 62)	55 (51.75; 62)	0.211

Abbreviations: PD = Parkinson's disease; HC = healthy controls
Data are presented as the median (1st quartile; 3rd quartile). * Group significant different at P < 0.050.

Supplementary figures



Supplementary figure 1. Correlations between performance on tablet tasks and clinical characteristics across groups (PD-OFF and HC). **A.** Total sliding time (ms) on the Single sliding task and MPT performance (s). **B.** Transition time (ms) on the Multi-direction sliding task with MPT performance (s). **C.** Transition time on the Multi-direction sliding task with scores on the dexterity questionnaire (DEXTQ-24). Filled circles = PD-OFF patients; unfilled circles = healthy controls.



Supplementary figure 2. Comparison performance on mobile phone task (MPT) between groups. Mann-Whitney U test compared patients with healthy controls. differences are indicated by square brackets. Wilcoxon Signed Ranks test compared medication conditions. * Group differences at $p < 0.050$; # Group differences at $P < 0.100$.

Supplementary Appendix

Smartphone specific questions (translated to English)

1. Do you have a smartphone or tablet? Yes / No
2. Do you play games on a smartphone or tablet daily? Yes / No
3. What do you use your smartphone or tablet for?
    a. Only for texting and calling
    b. Internet: reading and sending e-mails, WhatsApp, reading the newspaper, …
    c. Games: sudoku, crossword puzzle, etc.
    d. Combination of the above

    If yes, which? _____
4. What kind of problems do you experience in using a smartphone or tablet?
    a. Tapping
    b. Double tapping
    c. Swiping
    d. Size of the icons
    e. Other: _____
    f. No problems