SUPPLEMENTARY MATERIALS

METHODS

Neuropsychological assessment

At T0, blinded and experienced neuropsychologists, performed a cognitive screening evaluation to both PD patients and the age- and sex-matched healthy controls. For PD-PIGD patients, we tailored our neuropsychological battery according to the specific guidelines for PD-Mild Cognitive Impairment (MCI) level II category.[1] Accordingly, our neuropsychological testing included at least two tests within each cognitive domain. In PD patients we investigated the following domains: global cognition with the MMSE;[2] memory with the digit span forward,[3] the Rey's Auditory Verbal Learning Test (RAVLT),[4] and the recall of the Rey-Osterrieth Complex Figure;[5] executive functions with the Ten-point Clock Drawing Test;[6] the Modified Card Sorting Test;[7] the phonemic and semantic verbal fluency tests;[8] attention and working memory with the attentive matrices,[9] the Trail Making Test (TMT),[10] and digit span backward;[11] visuospatial abilities with the copy of the Rey-Osterrieth Complex Figure,[4] the freehand copying of drawings with and without landmarks,[4] the Benton judgment of line orientation test,[12] and the visuospatial subtests of the Addenbrooke's Cognitive Examination (ACE-R);[13] language with the confrontation naming subtests of the BADA battery,[14] and the token test;[15] mood and behaviour with the Beck Depression Inventory (BDI),[16] the Hamilton Depression Rating Scale (HDRS),[17] the Hamilton anxiety rating scale (HAMA),[18] the Apathy Rating Scale,[19] the Snaith-Hamilton Pleasure Scale (SHAPS),[20] and the Questionnaire for Impulsive-Compulsive Disorders in Parkinson's Disease-Rating Scale (QUIP-RS).[21] The Neuropsychiatric Inventory (NPI)[22] was administered to the caregivers for having further information on patient behaviour. The group of old healthy controls underwent the same neuropsychological evaluation, except for Rey-Osterrieth Complex Figure, BADA subtests, Benton Judgment of Line Orientation Test, ACE-R visuospatial subtests, Ten-point Clock drawing test, HAMA, QUIP-RS, NPI and HDRS scales.

References

1. Litvan I, Goldman JG, Troster AI, Schmand BA, Weintraub D, Petersen RC, Mollenhauer B, Adler CH, Marder K, Williams-Gray CH, Aarsland D, Kulisevsky J, Rodriguez-Oroz MC, Burn DJ, Barker RA, Emre M (2012) Diagnostic criteria for mild cognitive impairment in Parkinson's disease: Movement Disorder Society Task Force guidelines. Mov Disord 27:349-356
2. Folstein MF, Folstein SE, McHugh PR (1975) "Mini-mental state". A practical method for grading the cognitive state of patients for the clinician. J Psychiatr Res 12:189-198
3. Orsini A, Grossi D, Capitani E, Laiacona M, Papagno C, Vallar G (1987) Verbal and spatial immediate memory span: normative data from 1355 adults and 1112 children. Ital J Neurol Sci 8:539-548
4. Carlesimo GA, Caltagirone C, Gainotti G (1996) The Mental Deterioration Battery: normative data, diagnostic reliability and qualitative analyses of cognitive impairment. The Group for the Standardization of the Mental Deterioration Battery. Eur Neurol 36:378-384
5. Caffarra P, Vezzadini G, Dieci F, Zonato F, Venneri A (2002) Rey-Osterrieth complex figure: normative values in an Italian population sample. Neurol Sci 22:443-447
6. Manos PJ (1999) Ten-point clock test sensitivity for Alzheimer's disease in patients with MMSE scores greater than 23. Int J Geriatr Psychiatry 14:454-458
7. Caffarra P, Vezzadini G, Dieci F, Zonato F, Venneri A (2004) Modified Card Sorting Test: normative data. J Clin Exp Neuropsychol 26:246-250
8. Novelli G, Papagno C, Capitani E, Laiacona M, et al. (1986) Tre test clinici di ricerca e produzione lessicale. Taratura su sogetti normali. [Three clinical tests to research and rate the lexical performance of normal subjects.]. Archivio di Psicologia, Neurologia e Psichiatria 47:477-506
9. Spinnler H GT (1987) Standardizzazione e taratura italiana di test neuropsicologici. Ital J Neurol Sci 8:1-120.
10. Giovagnoli AR, Del Pesce M, Mascheroni S, Simoncelli M, Laiacona M, Capitani E (1996) Trail making test: normative values from 287 normal adult controls. Ital J Neurol Sci 17:305-309
11. Monaco M, Costa A, Caltagirone C, Carlesimo GA (2013) Forward and backward span for verbal and visuo-spatial data: standardization and normative data from an Italian adult population. Neurol Sci 34:749-754
12. Qualls CE, Bliwise NG, Stringer AY (2000) Short forms of the Benton Judgment of Line Orientation Test: development and psychometric properties. Archives of clinical neuropsychology : the official journal of the National Academy of Neuropsychologists 15:159-163
13. Mioshi E, Dawson K, Mitchell J, Arnold R, Hodges JR (2006) The Addenbrooke's Cognitive Examination Revised (ACE-R): a brief cognitive test battery for dementia screening. Int J Geriatr Psychiatry 21:1078-1085
14. Miceli G, Laudanna A, Burani C, Capasso R (1994) Batteria per l'analis dei deficit afasici B.A.D.A. [B.A.D.A. A battery for the assessment of aphasic disorders]. Roma: CEPSAG
15. De Renzi E, Vignolo LA (1962) The token test: A sensitive test to detect receptive disturbances in aphasics. Brain 85:665-678
16. Beck AT, Ward CH, Mendelson M, Mock J, Erbaugh J (1961) An inventory for measuring depression. Arch Gen Psychiatry 4:561-571
17. Hamilton M (1960) A rating scale for depression. Journal of neurology, neurosurgery, and psychiatry 23:56-62
18. Hamilton M (1959) The assessment of anxiety states by rating. Br J Med Psychol 32:50-55

19. Starkstein SE, Merello M, Jorge R, Brockman S, Bruce D, Power B (2009) The syndromal validity and nosological position of apathy in Parkinson's disease. Movement disorders : official journal of the Movement Disorder Society 24:1211-1216
20. Snaith RP, Hamilton M, Morley S, Humayan A, Hargreaves D, Trigwell P (2018) A Scale for the Assessment of Hedonic Tone the Snaith–Hamilton Pleasure Scale. British Journal of Psychiatry 167:99-103
21. Weintraub D, Mamikonyan E, Papay K, Shea JA, Xie SX, Siderowf A (2012) Questionnaire for Impulsive-Compulsive Disorders in Parkinson's Disease-Rating Scale. Movement disorders : official journal of the Movement Disorder Society 27:242-247
22. Cummings JL, Mega M, Gray K, Rosenberg-Thompson S, Carusi DA, Gornbein J (1994) The Neuropsychiatric Inventory: comprehensive assessment of psychopathology in dementia. Neurology 44:2308-2314

Supplementary Table 1. Summary of the selected CANTAB neuropsychological battery tests.

Cognitive CANTAB sub-tests	Cognitive domain	Outcome measures	Administration Modality
Motor Screening Task (MOT)	Sensorimotor function and comprehension	• Response latency • Accuracy	Coloured crosses are presented on the screen (one at a time). Participants must press the cross as quickly and accurately as possible.
Attention Switching Task (AST)	Multitasking ability	Ability to manage multitasking and interference of incongruent task-irrelevant information in terms of: • Response latency • Accuracy	An arrow is displayed on either side of the screen (left or right) and can point in either direction (left or right). Participants must select the left or right button on the screen according to "the side on which the arrow appeared" or the "direction in which the arrow was pointing". The test is divided in single *vs* multitasking blocks.
One Touch Stockings of Cambridge (OTS)	Planning ability	• Number of problems solved on first choice • Response latency	Two displays containing three coloured balls held in stockings or socks are presented. The experimenter first demonstrates how to move the balls in the lower display to copy the above pattern. Afterwards, the participant must work out how many moves the solutions require to copy the above display.
Spatial Recognition Memory (SRM)	Visuo-spatial recognition memory	• Number of correct trials • Percentage of correct trials • Response latency	Participants are presented with a white square, which appears in a sequence at five different locations on the screen. Afterwards, the participants might choose which square (among pairs) he/she has previously seen.
Spatial Working Memory (SWM)	Working memory and strategy	• Strategy in completing the task • Working memory errors	A number of coloured boxes appear on the screen, and the aim is that by selecting the boxes and using an elimination strategy, the

			participants should find one yellow “token” in each of a number of boxes. The participants need to use the tokens to fill up an empty column on the right section of the screen.

Supplementary Table 2. Neuropsychological features of PD-PIGD patients and healthy controls at baseline.

Variable	HC (N=23)	All PD-PIGD (N=21)	*p* all PD-PIGD *vs* HC	DUAL-TASK group (N=10)	DUAL-TASK + AOT-MI group (N=11)	*p* DUAL-TASK group *vs* DUAL-TASK + AOT-MI group
MMSE	29.23 ± 0.87 (27-30)	28.05 ± 1.98 (24.00-30.00)	**0.04**	28.00 ± 1.63 (24.00-30.00)	28.09 ± 2.34 (24.00-30.00)	0.45
MEMORY						
RAVLT - Immediate recall	49.50 ± 10.76 (29-67)	41.57 ± 11.77 (20.00-57.00)	**0.04**	47.00 ± 7.48 (31.00-57.00)	36.64 ± 13.05 (20.00-57.00)	0.057
RAVLT - Delayed recall	10.41 ± 2.48 (6-14)	8.24 ± 3.75 (0.00-14.00)	0.06	9.70 ± 3.20 (3.00-14.00)	6.91 ± 3.85 (0.00-12.00)	0.08
RAVLT – Recognition	14.18 ± 0.91 (12-15)	13.19 ± 2.86 (4.00-15.00)	0.44	14.20 ± 1.23 (11.00-15.00)	12.27 ± 3.61 (4.00-15.00)	0.12
Digit span forward	6.32 ± 1.13 (4-8)	5.57 ± 1.21 (4.00-7.00)	0.07	5.80 ± 1.13 (4.00-7.00)	5.36 ± 1.29 (4.00-7.00)	0.44
ROCF - Recall	-	14.71 ± 5.83 (4.00-24.00)	-	15.15 ± 7.05 (4.00-24.00)	14.32 ± 4.79 (5.00-22.50)	0.50
LANGUAGE						
Token Test	33.73 ± 2.12 (28.0-36.0)	33.05 ± 1.72 (29.00-35.00)	0.10	33.30 ± 1.78 (29.50-35.00)	32.82 ± 1.72 (29.00-35.00)	0.41
BADA - Names	-	29.52 ± 0.68 (28.00-30.00)	-	29.70 ± 0.48 (29.00-30.00)	29.36 ± 0.80 (28.00-30.00)	0.35
BADA - Verbs	-	27.09 ± 1.37 (22.00-28.00)	-	26.90 ± 1.85 (22.00-28.00)	27.27 ± 0.79 (26.00-28.00)	0.97
VISUO-SPATIAL ABILITIES						
ROCF - Copy	-	27.29 ± 6.12 (8.00-36.00)	-	26.35 ± 7.06 (8.00-34.00)	28.14 ± 5.32 (18.00-36.00)	0.62
Copy of drawings - Freehand	10.41 ± 1.05 (9-12)	10.09 ± 1.58 (6.00-12.00)	0.67	10.40 ± 1.90 (6.00-12.00)	9.82 ± 1.25 (7.00-12.00)	0.22
Copy of drawings - with landmarks	68.23 ± 2.11 (63-70)	64.38 ± 6.89 (47.00-70.00)	**0.03**	65.80 ± 7.11 (47.00-70.00)	63.09 ± 6.74 (48.00-70.00)	0.14

Benton Judgment of Line Orientation Test	-	15.30 ± 3.52 (9.00-20.00)	-	15.89 ± 2.76 (11.00-19.00)	14.82 ± 4.12 (9.00-20.00)	0.59
ACE-R, visuospatial	-	14.19 ± 1.66 (9.00-16.00)	-	13.90 ± 2.02 (9.00-16.00)	14.45 ± 1.29 (12.00-16.00)	0.55
EXECUTIVE FUNCTIONS						
CDT	-	7.67 ± 2.98 (1.00-10.00)	-	7.70 ± 3.40 (1.00-10.00)	7.64 ± 2.73 (2.00-10.00)	0.61
MCST Categories	4.36 ± 1.14 (3-6)	4.05 ± 1.69 (0.00-6.00)	0.83	4.40 ± 1.64 (0.00-6.00)	3.73 ± 1.74 (0.00-6.00)	0.18
Phonemic fluency	39.41 ± 8.16 (18-54)	35.38 ± 10.79 (9.00-58.00)	0.07	35.20 ± 6.23 (26.00-45.00)	35.54 ± 14.06 (9.00-58.00)	0.75
Semantic fluency	50.41 ± 9.30 (26-65)	43.14 ± 11.58 (18.00-62.00)	**0.02**	43.70 ± 10.74 (23.00-62.00)	42.64 ± 12.80 (18.00-61.00)	0.94
ATTENTION AND WORKING MEMORY						
Attentive matrices	54.00 ± 4.73 (40-60)	50.19 ± 6.19 (37.00-57.00)	**0.03**	50.00 ± 6.38 (37.00-57.00)	50.36 ± 6.33 (38.00-57.00)	0.83
TMT-A	29.89 ± 9.72 (16-52)	50.21 ± 26.73 (28.00-136.00)	**<0.01**	46.37 ± 19.11 (28.00-93.00)	53.70 ± 32.74 (28.00-136.00)	0.78
TMT-B	92.86 ± 33.16 (47.47-172.00)	129.80 ± 42.45 (72.00208.00)	**<0.01**	119.43 ± 44.38 (72.00-208.00)	140.17 ± 40.23 (94.00-198.00)	0.35
TMT-B-A	62.98 ± 27.36 (24-139)	88.10 ± 34.82 (44.00-160.00)	**0.01**	78.24 ± 36.68 (44.00-160.00)	97.96 ± 31.82 (59.00-154.00)	0.14
Digit span backward	4.86 ± 1.17 (3-7)	4.29 ± 1.38 (2.00-8.00)	0.13	4.40 ± 0.96 (3.00-6.00)	4.18 ± 1.72 (2.00-8.00)	0.45
MOOD						
BDI	7.50 ± 5.46 (0-20)	9.14 ± 6.02 (1.00-22.00)	0.13	12.00 ± 7.41 (2.00-22.00)	6.54 ± 2.73 (1.00-10.00)	0.09
HAMA	-	5.19 ± 3.64 (0.00-11.00)	-	5.90 ± 4.36 (0.00-11.00)	4.54 ± 2.91 (1.00-10.00)	0.55
ARS	8.00 ± 5.63 (0-19)	8.67 ± 4.29 (1.00-14.00)	0.54	9.80 ± 3.70 (4.00-13.00)	7.64 ± 4.69 (1.00-14.00)	0.43
QUIP-RS	-	6.10 ± 9.02	-	4.56 ± 8.25	7.50 ± 9.89	0.29

		(0.00-30.00)		(0.00-19.00)	(0.00-30.00)	
SHAPS 16 items	55.95 ± 3.95 (46-62)	51.16 ± 13.35 (0.00-64.00)	0.07	47.40 ± 17.42 (0.00-60.00)	55.33 ± 4.69 (50.00-64.00)	0.19
NPI	-	8.87 ± 7.34 (0.00-19.00)	-	9.80 ± 8.17 (2.00-19.00)	7.33 ± 7.02 (0.00-14.00)	0.65
HDRS	-	4.69 ± 2.75 (1.00-11.00)	-	5.67 ± 3.88 (2.00-11.00)	4.10 ± 1.79 (1.00-7.00)	0.70

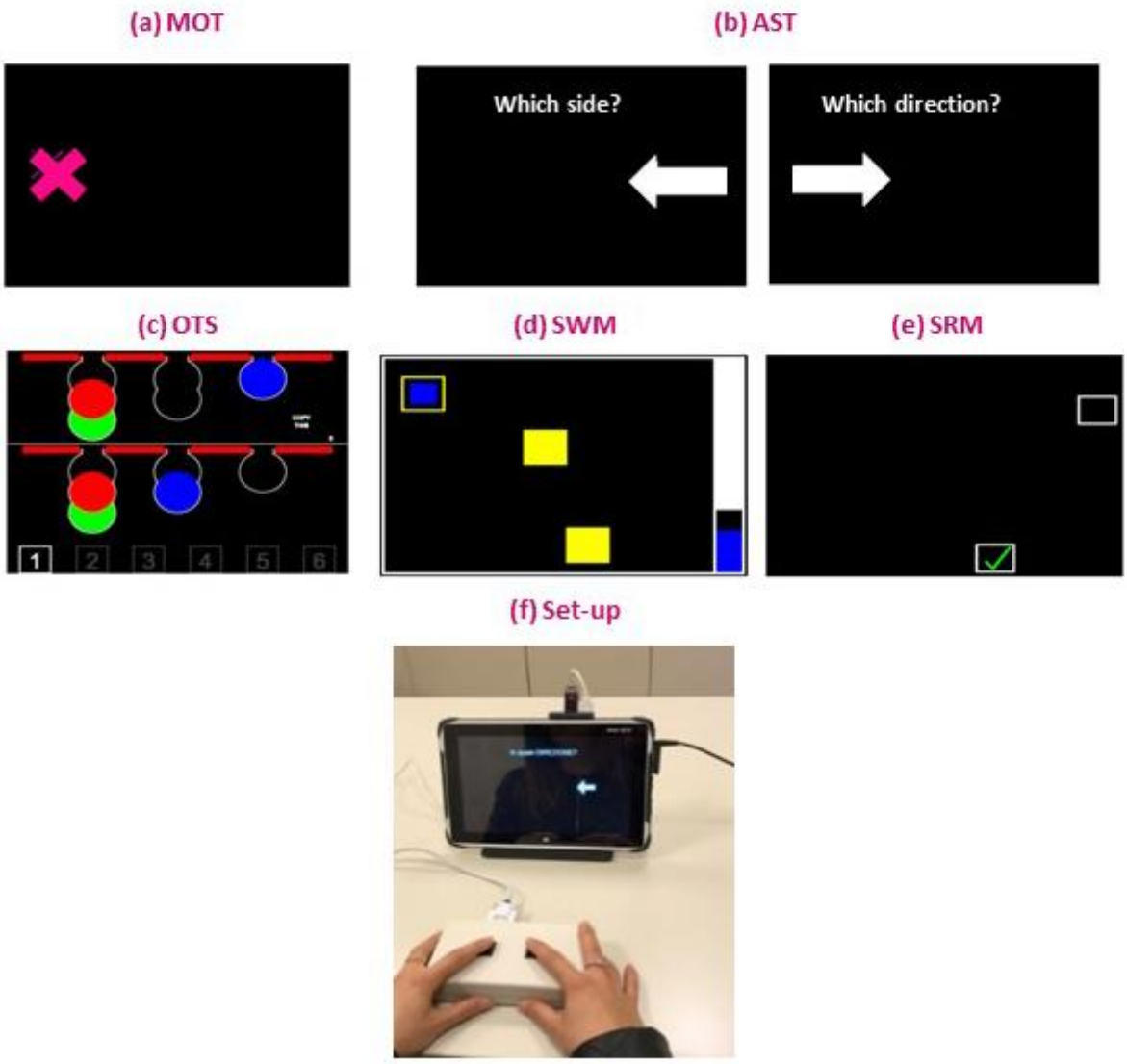
Values are mean ± standard deviation in the first row and minimum-maximum values in the second row. *p* values refer to Mann-Whitney U-test. Statistical significance was accepted for values of p <0.05. ***Abbreviations:*** *ACE-R= Addenbrooke's Cognitive Examination Revised; AOT-MI= action observation and motor-imagery; ARS= Apathy rating scale; BADA= Battery for Assessment of Aphasic Disorders; BDI= Beck Depression Inventory; CDT=Clock Drawing Test; HAMA= Hamilton Anxiety rating Scale; HC= healthy controls; HDRS= Hamilton Rating Scale for Depression; MCST= Modified Card Sorting test; MMSE= Mini Mental State Examination; N= number; NPI= Neuropsychiatric Inventory; PD= Parkinson's disease; PIGD= postural instability and gait disorders phenotype; RAVLT= Rey Auditory Verbal Learning Test; ROCF= Rey-Osterrieth Complex Figure; QUIP-RS= Questionnaire for Impulsive-Compulsive Disorders in Parkinson's Disease–Rating Scale; SHAPS= Snaith-Hamilton Pleasure Scale; TMT= Trail Making Test.*

Supplementary Table 3. Sociodemographic, clinical and CANTAB variables of those PD-PIGD patients with longitudinal RS-fMRI sequence and CANTAB assessments at baseline.

	DUAL-TASK group	**DUAL-TASK+ AOT-MI group**	***p* PD DUAL-TASK *vs* PD DUAL-TASK+AOT-MI**
N	9	8	-
Sociodemographic characteristics			
Age [years]	63.13 ± 7.09 (53.39-77.28)	65.71 ± 4.67 58.57-72.10	0.25
Sex [M/F]	7/2	6/2	0.39
Education [years]	11.56 ± 4.85 (6.00-20.00)	13.25 ± 2.71 9.00-17.00	0.28
PD duration [years]	7.67 ± 3.80 (2.00-13.00)	8.50 ± 4.10 3.00-16.00	0.70
Clinical characteristics			
H&Y [ON state]	2.28 ± 0.36 2.00-3.00	2.31 ± 0.37 2.00-3.00	0.83
H&Y [OFF state]	2.33 ± 0.35 2.00-3.00	2.44 ± 0.42 2.00-3.00	0.60
UPDRS-II	10.56 ± 2.51 7.00-14.00	9.13 ± 4.99 1.00-17.00	0.41
UPDRS-III [ON state]	27.00 ± 8.44 13.00-39.00	21.94 ± 6.84 14.00-33.00	0.18
UPDRS-III [OFF state]	30.56 ± 8.22 16.00-42.00	28.25 ± 7.79 18.00-38.00	0.66
MCI [yes/no]	1/8	1/7	1.00
CANTAB variables			
AST, percent total correct trials [%]	85.31 ± 6.84 75.62-96.25	90.52 ± 6.26 83.75-96.87	0.20
AST, percent total correct trials (simple condition) [%]	89.21 ± 8.45 75.00-100.00	96.25 ± 2.96 92.50-100.00	0.14
AST, percent total correct trials	81.40 ± 6.35	84.79 ± 9.66	0.56

(set-shifting condition) [%]	73.75-92.50	73.75-95.00	
AST, mean response latency (simple condition) [msec]	799.34 ± 134.71 612.56-982.31	681.84 ± 105.69 554.91-875.08	0.08
AST, mean response latency (set-shifting condition) [msec]	876.34 ± 161.71 697.02-1100.45	773.84 ± 142.40 605.61-967.54	0.14
MOT, mean response latency [msec]	778.10 ± 214.75 552.80-1102.80	715.56 ± 146.53 528.60-951.90	0.56
OTS, first choice [errors]	5.75 ± 2.71 2.00-9.00	4.71 ± 2.56 1.00-9.00	0.64
SRM, percent total correct trials [%]	72.50 ± 13.88 45.00-90.00	71.66 ± 13.29 55.00-95.00	0.65
SRM, mean response latency [msec]	3021.09 ± 955.97 1825.66-4874.46	2558.16 ± 955.26 1569.40-4185.50	0.42
SWM [total errors]	25.25 ± 6.31 16.00-37.00	14.66 ± 10.01 1.00-27.00	0.08
SWM, strategy [accuracy score*]	18.62 ±1.99 16.00-21.00	16.00-3.09 11.00-20.00	0.08

Values are mean ± standard deviation in the first row and minimum-maximum values in the second row. Categorical variables are reported as frequency. *p* values refer to Mann-Whitney U Test or Fisher's exact test for categorical variables. ***Abbreviations:*** *AOT-MI=action observation and motor-imagery; AST=Attention Switching Task; CANTAB=Cambridge Neuropsychological Automated Test Battery; H&Y=Hoehn and Yahr score; MCI=Mild Cognitive Impairment; M/F=male/female; MOT=Motor Screening Task; msec=milliseconds; N=number; OTS=One Touch Stockings of Cambridge; PD=Parkinson's Disease; PIGD=postural instability and gait disorders; SRM=Spatial Recognition Memory; SWM=Spatial Working Memory; UPDRS=Unified Parkinson's Disease Rating Scale. *higher scores indicate poor use of the best strategy, while lower scores indicate good strategy use.*



Supplementary Figure 1. Schematic representation of CANTAB sub-tests: (a) Motor Screening Test; (b) Attention Switching Task; (c) One Touch Stockings of Cambridge; (d) Spatial Working Memory; (e) Spatial Recognition Memory and (f) example of CANTAB set-up.