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Research Paper

Cognition and action: a latent variable approach to study contributions of executive functions to motor control in older adults

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ABSTRACT

Aging is associated with profound alterations in motor control that may be exacerbated by age-related executive functioning decline. Executive functions span multiple facets including inhibition (suppressing unwanted response tendencies), shifting (switching between cognitive operations), and updating (managing working memory content). However, comprehensive studies regarding the contributions of single facets of executive functioning to movement control in older adults are still lacking. A battery of nine neuropsychological tasks was administered to *n* = 92 older adults in order to derive latent factors for inhibition, shifting, and updating by structural equation modeling. A bimanual task was used to assess complex motor control. A sample of *n* = 26 young adults served as a control group to verify age-related performance differences. In older adults, structural equation models revealed that performance on the most challenging condition of the complex motor task was best predicted by the updating factor and by general executive functioning performance. These data suggest a central role for working memory updating in complex motor performance and contribute to our understanding of how individual differences in executive functioning relate to movement control in older adults.

INTRODUCTION

Aging is associated with a motor functioning decline that must be addressed to promote healthy and active living throughout the lifespan [1, 2]. Evidence from dual-task paradigms and findings of cortical hyper-activation from functional neuroimaging suggest motor control to become less automated and more effortful during aging [1–7]. Specifically, older adults have been suggested to engage higher-order cognition (executive functions) to a larger extent than younger adults when performing complex motor tasks, possibly reflecting the recruitment of generic brain regions to support motor performance [3–5, 8–10]. Hence, intact executive functioning may be particularly crucial for older adults when performing complex motor control tasks, such as bimanual coordination [6, 11, 12]. Indeed, age-associated bimanual coordination changes have been found in various paradigms [1]. Similar to motor performance, executive functions decline during aging [13–16]. Such executive functioning decline might exacerbate age-related difficulties in motor control and should therefore be taken into account when investigating age-related changes in motor functions.

Executive functions are a set of dissimilar capacities rather than one unitary ability. Three key facets of executive functioning are inhibition (i.e., suppressing unwanted response tendencies), shifting (i.e., switching between cognitive operations), and updating (i.e., managing working memory content) [8, 17, 18]. Despite this heterogeneity of executive functions and their hypothesized link with motor abilities especially during aging, few studies have addressed how individual differences in multiple facets of executive functioning are associated with complex motor control in older adults. However, such a multifaceted approach to executive functioning (i.e., one that takes into account multiple dissimilar domains of executive functioning) is crucial to differentiate between the contributions of distinct executive functions to individual differences in motor performance. Bangert and colleagues reported bimanual circle-drawing performance to be related to older adults' working memory (assessed as backward digit span) [19]. This relationship was restricted to the most challenging task condition, and no significant relationship was found with inhibition and shifting performance. Similarly, Corti and colleagues examined associations between executive functioning and fine motor control (assessed by the Purdue Pegboard Test) in older adults across several executive functioning domains (working memory, set-shifting, planning) [20]. They found performance on a single task assessing planning abilities (a higher-order executive function [8]) to be the most consistent predictor of motor performance in older adults across unimanual and bimanual conditions.

Taken together, the available evidence regarding the link between distinct facets of executive and motor control in older adults is still scarce and fragmented, and especially studies taking into account the multifaceted nature of executive functioning are lacking. In addition, the available studies address contributions of executive functions to complex motor control on the level of single tasks (i.e., reporting the performance on one particular task as an indicator for the corresponding executive function). This represents a critical methodological limitation because every cognitive laboratory task is 'impure', i.e. necessarily captures variability that is unspecific to the function under investigation (e.g., visual processing), hampering both reliability and generalizability. This task-impurity problem can be mitigated by the use of multiple tasks for every cognitive domain under investigation. The shared variance among tasks representing the same function can then be modeled as latent factors [9, 17, 18]. Such latent variable approaches are therefore particularly suitable for the assessment of executive functions, but have not been applied to study the individual contributions of dissimilar executive functioning domains to complex motor control in older adults [13, 16–18, 21–25].

Here, we investigate how distinct facets of executive functioning contribute to complex movement control in older adults. For this purpose, we use a bimanual tracking task (BTT [26]) which is sensitive to age-associated changes [27–32]. The BTT requires participants to perform rotational movements with both hands simultaneously (Figure 1A). The complex BTT-condition requires one hand to perform periodic switches of the rotational direction whilst the other hand needs to maintain a continuous rotational movement (Figure 1C). There are strong conceptual reasons to expect contributions of executive functions to BTT-performance as the BTT and executive functioning paradigms share critical task demands. Specifically, conceptual overlap with response-inhibition tasks involves selectively suppressing unwanted movements of one hand while continuing the other hand's movement. Similarly, the BTT converges with shifting tasks in that performers need to shift attention from keeping both hands moving to reversing the movement of one hand selectively. Finally, overlaps with working memory tasks involve repeated updating of the prevailing movement pattern and monitoring the two hand movements simultaneously whilst comparing performance to the task goal (here: comparing the position of a cursor to a target on the screen).

These conceptual overlaps justify to assume that inhibition, shifting, and updating are all substantially related to motor performance. However, to determine if any of these executive functions contributes particularly strongly to motor control, they need to be studied simultaneously (i.e., in a multifaceted approach) and with the necessary attention toward the problems arising from task impurity (i.e., in a latent variable approach). Such comprehensive data—taking into account both the multifaceted nature of executive functioning and the task-impurity problem—are currently lacking. This study is the first to examine the contributions of multiple facets of executive functioning to complex motor performance in older adults by using latent variable modeling, thereby creating a basis for a more detailed understanding of the link between executive abilities and movement control in aging.

MATERIALS AND METHODS

Participants

One hundred and thirteen older adults (≥ 60 years) were recruited from the area of Leuven. We chose to retain only complete datasets for analysis and therefore excluded the following cases: two participants who opted out of the complex motor task, sixteen participants for insufficient adherence to task instructions on at least one neuropsychological task (as evidenced by performance that was indistinguishable from chance level; see Supplementary Materials), one participant because of recording failure, two participants because testing was aborted after one session (see Supplementary

Materials) due to COVID-19 containment procedures. The effective sample size was n = 92 older adults (55 female, 37 male; 4 left-handed, 11 ambidextrous, 77 right-handed [33, 34]). Normal (or corrected-to-normal) vision was required for inclusion. Exclusion criteria were current intake of psychoactive medication and the presence of psychiatric/neurological disorders, upper limb injury that would have interfered with BTT-completion, and/or contraindications for magnetic resonance imaging (this study was part of a larger project; neuroimaging results will be reported elsewhere). None of the participants showed signs of mild cognitive impairment on the Montreal Cognitive Assessment (MoCA; range: 24-30 [35, 36]).

Thirty-three young adults were recruited to verify the presence of age-associated executive and motor performance differences. Seven participants were excluded for insufficient adherence to task instructions on at least one neuropsychological task (see Supplementary Materials). The effective sample size for young adults was n = 26 (16 female, 10 male; 4 left-handed, 4 ambidextrous, 18 right-handed). Apart from the targeted age range (18-40 years), inclusion criteria and procedures were identical for the groups. Table 1 displays the sample characteristics.

The study was reviewed and approved by the Ethics Committee Research UZ/KU Leuven. All participants gave written informed consent to participate and were offered € 100 as compensation. The dataset and code are available on https://www.osf.io/5v2rz.

Procedure

Neuropsychological tasks

Executive function assessment followed the protocol of Friedman and colleagues, with minor modifications [37]. Inhibition, shifting, and updating were each examined by three well-established and validated tasks (inhibition: antisaccade task (AT) [37–40], number-Stroop task (NST) [37, 41–43], stop-signal task (SST) [37, 39, 44, 45]; shifting: category-switch task (CAST)

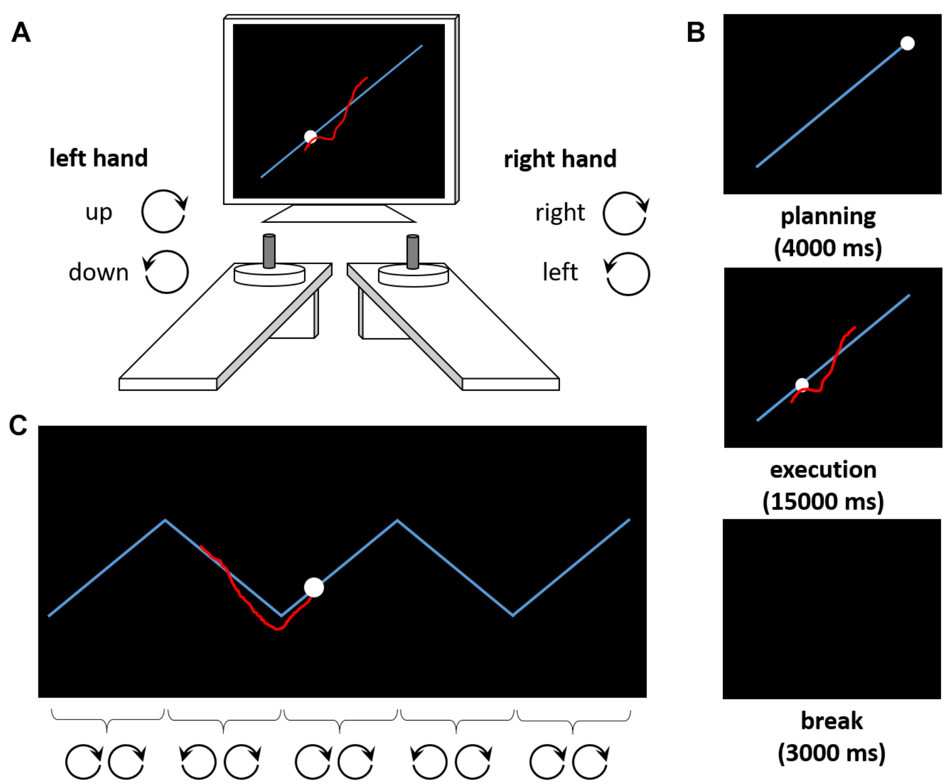

Figure 1. The Bimanual Tracking Task (BTT). (**A**) The task setup consists of two dials placed in front of a computer screen. Participants are asked to rotate both dials simultaneously to track a moving dot along a target line. Rotating the left dial clockwise (counterclockwise) causes the red cursor to move upward (downward) along the Y-axis, whereas rotating the right dial clockwise (counterclockwise) causes the cursor to move to the right (left) along the X-axis. (**B**) Exemplary trial sequence. After a planning phase of 4000 ms, the movement is executed (15000 ms). A break of 3000 ms precedes the next trial. (**C**) Exemplary trial from the zigzag condition. The target trajectory requires periodic switches in the rotation of one (here: left) hand, whereas the other (here: right) hand should continue its movement. For illustration purposes, the correct rotation directions for both hands are indicated for each segment of the zigzag trajectory here.

Table 1. Sociodemographic characteristics and background information of the study sample.

	Young adults (*n* = 26)	Older adults (*n* = 92)	
	M (*SD*)	*M* (*SD*)	*d* [95%-CI]
Age (years)[a]	23.35 (4.47)	67.99 (4.61)	9.74 [8.41; 11.08]
Education (years)	18.98 (1.91)	18.13 (2.67)	-0.34 [-0.79; 0.11]
MoCA	28.96 (1.48)	27.73 (1.77)	-0.72 [-1.17; 0.27]
PPVT-III-NL	111.19 (8.00)	109.35 (8.73)	-0.22 [-0.66; 0.23]
BSI-18 Global Severity Index	5.73 (4.34)	3.79 (4.90)	-0.40 [-0.85; 0.04]
Depression	1.62 (1.63)	0.82 (1.65)	-0.49 [-0.93; -0.04]
Anxiety	2.50 (2.21)	1.71 (2.63)	-0.31 [-0.75; 0.13]
Somatization	1.62 (2.40)	1.27 (1.85)	-0.17 [-0.61; 0.27]
MBQ[b] Total	8.32 (1.24)	8.30 (1.31)	-
Work / Household	2.16 (0.53)	1.93 (0.35)	-
Sport	3.13 (0.73)	3.15 (0.67)	-
Leisure	3.03 (0.59)	3.21 (0.64)	-
IPAQ Total	4218.94 (3703.67)	5210.64 (4513.12)	0.23 [-0.21; 0.67]
Work	935.10 (2009.01)	772.85 (2643.13)	-0.06 [-0.50; 0.38]
Transport	1401.98 (1146.70)	1193.84 (1259.55)	-0.17 [-0.61; 0.27]
House	481.92 (1009.80)	1886.90 (2397.35)	0.65 [0.20; 1.09]
Leisure	1399.94 (1556.30)	1357.04 (1683.82)	-0.03 [-0.47; 0.41]
Sitting	2905.20 (1183.25)	2232.81 (1046.47)	-0.62 [-1.08; -0.16]
RAND-36			
Physical Functioning	98.46 (3.68)	87.39 (13.27)	-0.93 [-1.39; -0.48]
Social Functioning	91.35 (13.59)	93.61 (13.17)	0.17 [-0.27; 0.61]
Role Limitations (Physical)	94.23 (14.68)	89.95 (26.22)	-0.18 [-0.62; 0.26]
Role Limitations (Emotional)	88.46 (26.57)	96.74 (12.16)	0.51 [0.06; 0.95]
Mental Health	74.15 (15.60)	81.13 (12.53)	0.53 [0.08; 0.97]
Vitality	64.42 (17.96)	74.57 (12.87)	0.72 [0.27; 1.17]
Pain	87.76 (12.66)	83.63 (17.73)	-0.25 [-0.69; 0.20]
General Health Perception	73.08 (13.72)	70.22 (14.52)	-0.20 [-0.64; 0.24]
Health Change	55.77 (19.12)	51.36 (16.31)	-0.26 [-0.70; 0.18]

Note: MoCA = Montreal Cognitive Assessment, higher scores indicate better cognitive status [36]; PPVT-III-NL = Dutch version of the Peabody Picture Vocabulary Test, higher scores indicate higher crystallized intelligence [46, 47]; BSI-18 = Brief Symptom Inventory, 18-item version, higher scores indicate higher symptom severity [48]; MBQ = Modified Baecke Questionnaire, higher scores indicate higher levels of physical activity [49]; IPAQ = International Physical Activity Questionnaire, higher scores indicate higher levels of physical activity (except for "sitting", where higher scores indicate lower levels of physical activity) [50]; RAND-36 = Short Form Health Survey, higher scores indicate better health-related well-being [51, 52]. [a] Effective age range: 18-37 years (young adults), 60-85 years (older adults). [b] Age-specific versions were used for older and young adults [53]. The scale "work" ("household") applies to young adults (older adults) only.

[37, 39, 54, 55], color-shape task (COST) [37, 39, 42, 56], number-letter task (NLT) [37, 39, 57]; updating: digit-span task (DST) [42, 58], keep track task (KTT) [37, 39, 59], spatial 2-back task (STT) [37, 39, 60]; see Supplementary Materials for details on timing and trial numbers). Neuropsychological tasks were programmed and controlled by OpenSesame version 3.2.6 [61]. Responses were collected on a standard QWERTY computer keyboard.

Motor task

Complex motor control was assessed using the BTT [26], which was controlled by LabView 2016 (National Instruments, Austin, TX). Participants tracked a moving dot on a target line on the computer screen by bimanually rotating two dials at a prescribed frequency. Clockwise (counterclockwise) rotations with the right hand caused the cursor to move to the right (left) on the computer screen. Clockwise (counterclockwise) rotations with the left hand caused the cursor to move upward (downward; Figure 1A). In the 'straight' condition, the target trajectory was a diagonal line (i.e., both dials should be rotated at the same speed in a constant direction, Figure 1B). In the 'complex' condition, the target trajectory was a zigzag line, with abrupt changes of direction [28, 32] (i.e., rotation direction in one hand should be maintained, whereas rotation direction of the other hand should be adjusted whenever the target dot changed its direction on the trajectory, Figure 1C; see Supplementary Materials for details on timing and trial numbers). The outcome measure was the average accuracy of the tracking performance across trials (see Supplementary Materials for calculation and technical details). Briefly, accuracy scores reflect how well the cursor is moved on top of or parallel to the target line at the same speed as the target dot. Accuracy decreases as a result of (a) too fast or too slow cursor movements, (b) movements away from the target line or in the wrong direction, or (c) cutting corners in the 'zigzag' condition.

Data analysis

The neuropsychological data were processed in SPSS 26 (IBM, Armonk, NY) to derive the outcome measures (see Supplementary Materials) [37]. BTT data were analyzed in Matlab 2019b (MathWorks, Natick, MA). Data analysis was performed in R 4.0.2 [62] in RStudio 1.3 (RStudio, Boston, MA), relying on the lavaan package version 0.6-7 [63] for structural equation modelling.

Age-associated differences in executive functions and motor performance

One-sided independent samples *t*-tests were used to verify the presence of age-associated differences between young and older adults in neuropsychological and motor tasks.

Relations between executive functions and motor performance in older adults

Structural equation models were defined to probe relations between complex motor control and inhibition, shifting, and updating. The outcomes of AT, NST, and SST were used as indicators for a latent inhibition factor. Similarly, the outcomes of CAST, COST, and NLT were used as indicators of shifting, and the outcomes of DST, KTT, and STT were used as indicators of updating. These latent factors were modeled as predictors of accuracy on the complex BTT-condition in older adults.

We first modeled inhibition, shifting, and updating as dissociable, but correlated factors ("correlated factors model") [17]. Next, we ran a model where a common executive functioning factor ("Common EF") accounts for shared variance across all indicators ("bifactor model"). For this model, shifting-specific and updating-specific factors were created based on the respective indicator tasks. These specific factors were modeled orthogonally to each other and to the Common EF factor, hence representing unique variance [18, 37]. Note that an inhibition-specific factor is not typically found when testing young adults, with mixed findings in older adults [9, 13, 16, 18, 22–25]. Hence, we also ran a model including an inhibition-specific factor to explore its presence in this sample. Finally, to assess whether the results were specific to the complex BTT-condition, we re-ran the models using the simple condition as a dependent variable.

RESULTS

Age-associated differences in executive functions and motor performance

We found executive and motor performance differences between young and older adults on all except two tasks (Table 2). On the COST, switch costs were numerically higher in older compared to young adults, but not significantly different. On the NST, older adults showed less susceptibility to response conflict compared to young adults. This can be explained by generally slowed reaction times (RTs) in older adults, which may have masked condition differences (congruent: M = 1003.35 ms; incongruent: M = 1092.14 ms), whereas RTs showed stronger modulations as a function of condition in young adults (congruent: M = 630.69 ms; incongruent: M = 800.81 ms). Hence, the NST may not be a suitable indicator of inhibition in this study, at least not for older adults, and should be interpreted cautiously.

Relations between executive functions and motor performance in older adults

Figure 2A displays Pearson correlations between the neuropsychological and motor tasks for the present sample of older adults. The neuropsychological tasks were mostly positively intercorrelated, with the exception of NST. The BTT correlated with various neuropsychological tasks. For comparison, Figure 2B displays zero-order correlations for the present sample of young adults.

The correlated factors model (Figure 3A) showed acceptable fit, $\chi^2(30)$ = 41.17, p = .084; CFI = .90; RMSEA = .06; SRMR = .07. The executive factors were intercorrelated (.53-.74, all p < .01). Updating significantly predicted complex BTT-performance, β =

Table 2. Outcome measures for the executive and motor tasks for young (n = 26) and older adults (n = 92).

task	*M*	*SD*	min	max	skewness	kurtosis	group difference
AT (proportion of correct responses in antisaccade blocks)							$t(116) = 7.15$
young	0.76	0.14	0.40	0.95	-0.74	-0.01	$p < .001$ $d = 1.59$
older	0.53	0.14	0.21	0.89	0.31	-0.09	[1.10; 2.07]
NST (median RTs for correct responses for incongruent minus congruent trials)							$t(116) = 3.44$
young	170.12 ms	72.67	-14.00	292.00	-0.52	-0.10	$p > .999$ $d = 0.76$
older	88.78 ms	113.86	-198.00	340.00	-0.26	-0.41	[0.31; 1.22]
SST (stop-signal RT)							$t(116) = -5.66$
young	222.96 ms	26.35	173.00	279.50	-0.11	-0.87	$p < .001$ $d = -1.26$
older	272.50 ms	42.28	140.08	404.44	-0.45	2.03	[-1.73; -0.79]
CAST (difference of median RTs between switch and repeat trials)							$t(116) = -3.74$
young	173.92 ms	99.89	-11.50	350.00	0.14	-1.00	$p < .001$ $d = -0.83$
older	348.30 ms	231.39	-62.50	1068.80	0.97	0.75	[-1.28; -0.38]
COST (difference of median RTs between switch and repeat trials)							$t(116) = -1.08$
young	290.89 ms	135.81	65.00	673.00	0.75	0.39	$p = .141$ $d = -0.24$
older	369.79 ms	363.94	-489.00	1631.33	1.22	2.09	[-0.68; 0.20]
NLT (difference of median RTs between switch and repeat trials)							$t(116) = -2.18$
young	306.26 ms	239.67	18.00	1042.14	1.26	1.32	$p = .016$ $d = -0.48$
older	416.68 ms	225.21	-53.50	1119.31	0.81	0.70	[-0.93; -0.04]
DST (total number of correct trials)							$t(116) = 5.88$
young	15.12	4.67	5.00	28.00	0.38	0.66	$p < .001$ $d = 1.31$
older	10.37	3.29	5.00	20.00	0.79	0.38	[0.83; 1.78]
KTT (proportion of correctly recalled words)							$t(116) = 5.73$
young	0.78	0.09	0.63	0.98	0.39	-0.16	$p < .001$ $d = 1.27$
older	0.65	0.11	0.32	0.95	-0.22	0.34	[0.80; 1.74]
STT (proportion of correct responses)							$t(116) = 5.35$
young	1.33	0.08	1.13	1.49	-0.40	0.49	$p < .001$ $d = 1.19$
older	1.20	0.12	0.91	1.40	-0.33	-0.53	[0.72; 1.65]
BTT-simple (percent coverage of the target line)							$t(116) = 4.58$
young	89.19 %	2.40	82.13	92.10	-1.04	0.60	$p < .001$ $d = 1.02$
older	84.98 %	4.50	73.14	91.92	-0.76	-0.02	[0.56; 1.48]
BTT-complex (percent coverage of the target line)							$t(116) = 8.09$
young	76.09 %	4.55	65.76	84.52	-0.28	-0.29	$p < .001$ $d = 1.80$
older	62.88 %	7.95	45.83	82.51	-0.12	-0.33	[1.30; 2.29]

Note: Values for the neuropsychological tasks are displayed after between-subjects trimming and transformation (see Supplementary Materials). Group differences are tested one-sided, hypothesizing better performance in young as compared to older adults. Confidence intervals indicate 95% confidence intervals for *d*.

.59, $p = .023$, 95%-CI [0.08; 1.09]. Inhibition and Shifting did not significantly predict complex BTT-performance ($\beta = .24$, $p = .593$, 95%-CI [-0.63; 1.10], and $\beta = -.17$, $p = .596$, 95%-CI [-0.79; 0.46], respectively).

The bifactor model (Figure 3B) showed a good fit, $\chi^2(27) = 24.42$, $p = .607$; CFI > .99; RMSEA < .01; SRMR = .06. Common EF predicted complex BTT-performance, $\beta = .58$, $p < .001$, 95%-CI [0.33; 0.82]. The updating-specific factor, but not the shifting-specific factor ($\beta = -.19$, $p = .289$, 95%-CI [-0.54; 0.16]), predicted additional unique variance in complex BTT-performance, $\beta = .32$, $p = .018$, 95%-CI [0.06; 0.59]. Adding an inhibition-specific factor to this bifactor model (not displayed) resulted in comparable model fit, $\chi^2(23) = 19.67$, $p = .662$; CFI > .99; RMSEA < .01; SRMR = .05. However, this inhibition-specific factor did not explain additional unique variance in complex BTT-performance above and beyond Common EF (β = .57, p < .001, 95%-CI [0.32; 0.82]) and the updating-specific factor (β = .32, p = .021, 95%-CI [0.05; 0.59]), β = .06, p = .724, 95%-CI [-0.27; 0.38].

When we re-ran the models using the simple BTT-condition as a dependent variable to assess whether the results were specific to the complex BTT-condition, the correlated factors model showed comparable fit to the initial version, $\chi^2(30)$ = 38.45, p = .139; CFI = .92; RMSEA = .06; SRMR = .07. Updating remained a significant predictor of motor performance, β = .57, p = .017, 95%-CI [0.10; 1.04]. For the bifactor model, fit indices were also comparable to the initial version, $\chi^2(27)$ = 25.83, p = .528; CFI > .99; RMSEA < .01; SRMR = .06. Common EF significantly predicted performance on the simple BTT-condition, β = .61, p < .001, 95%-CI [0.36; 0.84]. However, in contrast to the complex BTT-condition, the updating-specific factor did not significantly predict additional variance in the simple BTT-condition, β = .20, p = .153, 95%-CI [-0.07; 0.47].

DISCUSSION

This study is the first to examine the contributions of individual differences in distinct facets of executive functioning to complex motor performance in older adults by latent variable modeling. A latent updating factor predicted complex motor performance, even when accounting for shared variance with other executive tasks. This updating factor reflected variance that is specific to working memory. General executive abilities also predicted motor performance. These results reveal a unique contribution of individual differences in the ability to monitor and manipulate working memory content to motor performance in older adults, but also highlight the dependence of motor control on general executive abilities.

The relationship between updating and motor performance in older adults may be explained by the fact that the complex BTT-condition overlaps with the demands posed by the tasks subsumed under updating in that it involves a high working memory load. Specifically, to successfully follow the zigzag trajectory on the screen, participants need to monitor and control the dissimilar movements of both hands simultaneously. While one hand needs to perform regular movement switches to reverse the rotation direction, the other hand should continue its movement with minimal interruption. In addition, the cursor location needs to be compared to the target position on the screen, calling for real-time adjustments, which arguably poses significant demands on working memory. In support of this

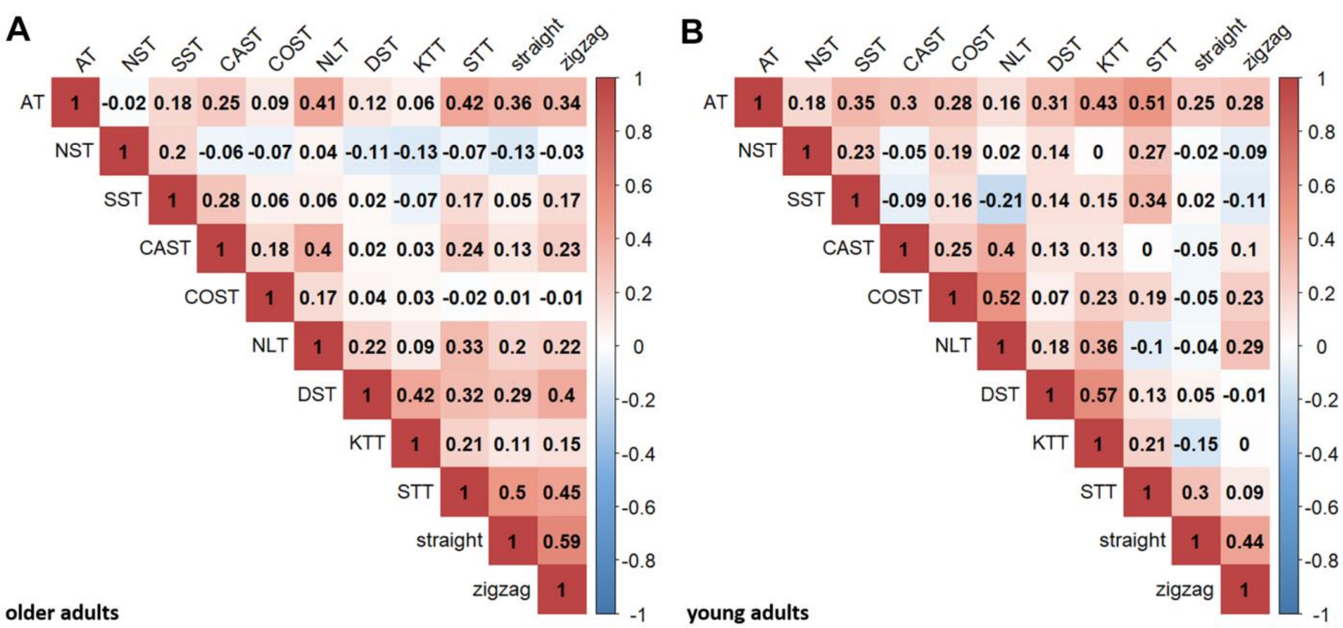

Figure 2. Pearson correlations between executive and motor tasks. Pearson correlation coefficients are shown for older (**A**) and young (**B**) adults for descriptive purposes (critical r-value for p < .05, uncorrected: .205 (older adults), .389 (young adults); critical r-value for p < .000909, Bonferroni-corrected (.05/55): .341 (older adults), .612 (young adults)). AT, NST, SST represent inhibition; CAST, COST, NLT represent shifting; DST, KTT, STT represent updating. "straight" and "zigzag" indicate the respective BTT-conditions. All tasks were transformed so that higher scores indicate better performance.

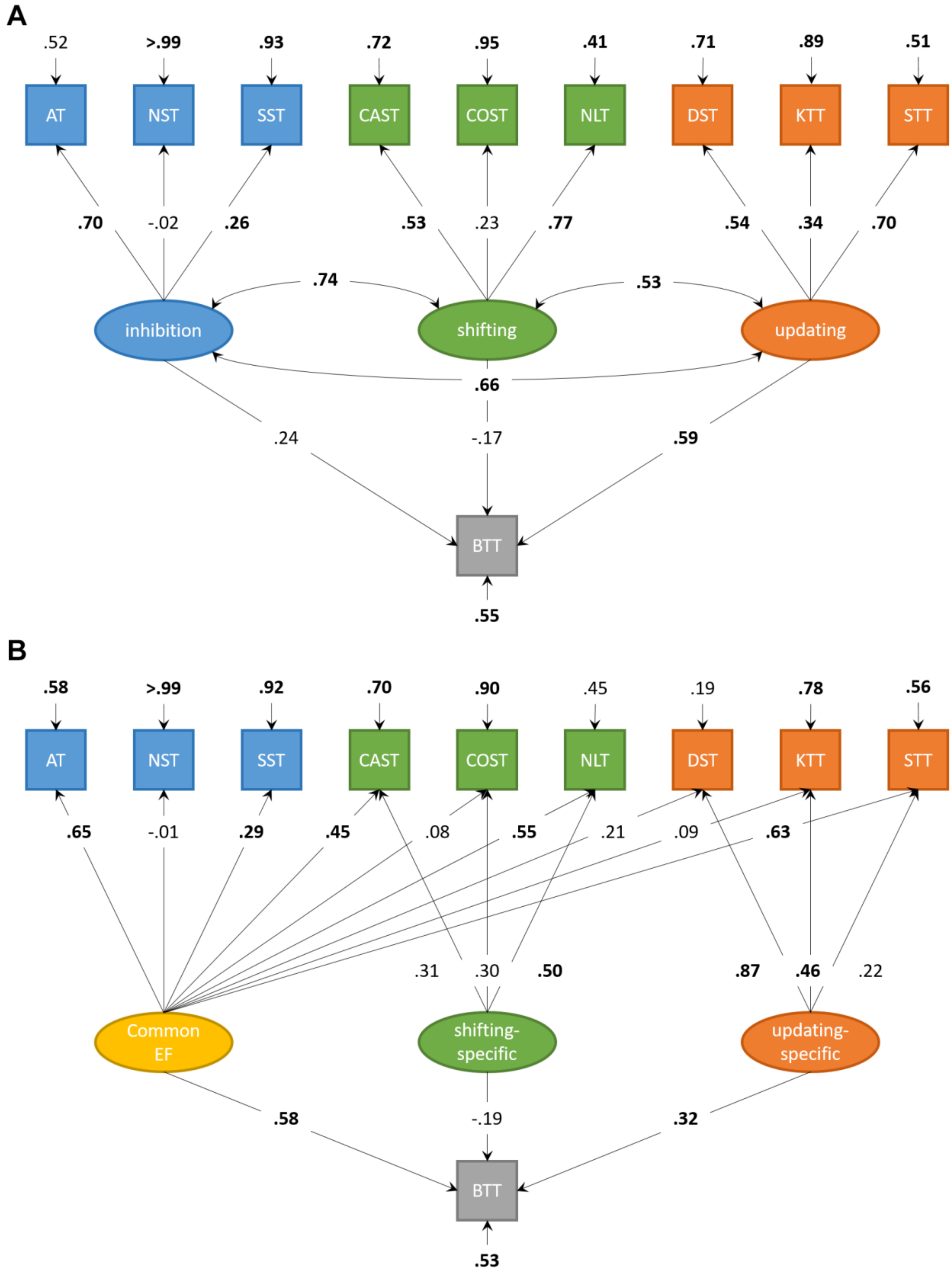

Figure 3. Structural equation models for executive functions and motor performance in older adults. (**A**) Structural equation model for correlated factors of inhibition, shifting, and updating. Updating significantly predicts performance on the complex condition of the bimanual coordination task in older adults. (**B**) Structural equation model with orthogonal factors, accounting for variance shared by all neuropsychological tasks (Common EF). Both Common EF and the updating-specific factor predict unique performance on the complex condition of the bimanual coordination task in older adults. Significant parameters are highlighted in boldface.

interpretation, the link between updating and motor performance did not remain significant for the simple BTT-condition without movement switches after accounting for Common EF. Our interpretation is also backed up by a previous report of correlations between challenging bimanual coordination tasks and working memory [19].

Latent factors reflecting shifting and inhibition did not significantly predict motor performance in this dataset. Shifting factors showed a numerically negative relationship with complex motor control, which is consistent with a proposed trade-off between stability and flexibility, where individuals with lower cognitive flexibility may be able to shield task performance more efficiently from external distractions compared to individuals with higher cognitive flexibility [9, 64]. Future studies could further examine this relationship in larger samples. We did not find evidence for inhibition-specific contributions to complex motor performance in this sample. In the correlated factors model, the inhibition factor showed a positive, but non-significant relationship with motor performance, which is broadly consistent with earlier reports based on findings on a single inhibition task [65]. In the bifactor model, the "inhibition"-specific factor mainly captured variability in NST (standardized factor loading: .59) and less from other inhibition tasks (AT: .02, SST: .38), and hence might not have reflected inhibition optimally. Given that earlier work did not find a separable inhibition factor at all in older adults [13, 22–24] (but see [16, 25]), future studies may further determine under which circumstances inhibition factors are distinguishable in older adults and how they contribute to motor control.

This study does not allow for a mechanistic interpretation of the link between updating and motor control in older adults [66]. However, longitudinal training studies could determine whether training-induced improvement of updating aids motor performance. If complex motor control could benefit from better updating ability (rather than merely coinciding with it), this would have important implications. First, it would allow for a more detailed understanding of the role of cognitive functions in motor control in general. Second, it would open up possibilities for designing cognitive training tools to ameliorate motor coordination in older adults.

When interpreting these data, some limitations should be considered. While the current sample size exceeds that of previous studies regarding similar research questions, it is still relatively small for structural equation modeling. This is partly due to our rigorous efforts to guarantee high data quality by implementing strict inclusion criteria based on sample characteristics and task performance. Specifically, insufficient performance on the SST led to the exclusion of a relatively high number of participants. The nature of the SST makes it challenging to avoid "waiting" for a potential stop-signal before reacting, imposing tolerance toward errors on the participant. Future studies should prevent performance-based exclusions by using an SST-version where waiting strategies are discouraged by design [67]. Moreover, the validity of the NST as an inhibition measure remains unclear in this dataset. Inspection of the data suggests that in older adults, RT differences between conditions were masked by generally slowed responding, reducing differences between congruent and incongruent conditions. This might be prevented in future work by manipulating congruency in a trial-wise, rather than block-wise manner and/or by introducing response-time pressure. While the NST did not capture much variance related to the other two inhibition tasks, the AT and SST could still be utilized as indicators of inhibition. Finally, note that the young control sample was recruited in order to verify the previously reported age-related between-groups task performance differences. Latent variable modeling of executive functioning in this group was beyond the scope of this study and would not have been possible due to sample size requirements. Age-related differences in the latent factor structure of executive functioning and their implications should be investigated in future work.

Taken together, this study sheds light on the interrelations between individual differences in multiple distinct facets of executive functioning and complex motor performance at older age. Importantly, we examined executive functioning using a latent variable approach, mitigating the limitations associated with single task assessments [17, 21]. In addition to a relation between motor performance and common executive abilities, our data suggest a specific link between older adults' capability to monitor and update working memory content and performing complex motor actions with both hands simultaneously. These findings extend our understanding of motor decline in aging and suggest new routes for designing cognitive training tools to preserve motor control across the lifespan.

Abbreviations

AT: antisaccade task; BSI-18: Brief Symptom Inventory, 18-item version; BTT: bimanual tracking task; CAST: category-switch task; common EF: common executive functioning factor; COST: color-shape task; DST: digit-span task; IPAQ: International Physical Activity Questionnaire; KTT: keep track task; MBQ: Modified Baecke Questionnaire; MoCA:

Montreal Cognitive Assessment; NLT: number-letter task; NST: number-Stroop task; PPVT-III-NL: Dutch version of the Peabody Picture Vocabulary Test; RAND-36: Short Form Health Survey; SST: stop-signal task; STT: spatial 2-back task.

AUTHOR CONTRIBUTIONS

Study conceptualization: CS, SPS; study design: CS, JS, FL, SPS; data collection: CS, JS; data analysis: CS, FL; interpretation of results: CS, JS, FL, GRN, SPS; manuscript draft: CS; critical revisions to the manuscript: JS, FL, GRN, SPS; approval of the final version of the manuscript: CS, JS, FL, GRN, SPS.

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CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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SUPPLEMENTARY MATERIALS

Supplementary Methods

Procedure

Neuropsychological tasks

Executive function assessment followed the protocol described by Friedman and colleagues, with some modifications [1]. Specifically, inhibition, shifting, and updating were each examined by three well-established and validated tasks. Neuropsychological tasks were programmed and controlled by OpenSesame version 3.2.6 [2]. Responses were collected on a standard QWERTY computer keyboard.

Inhibition

Versions of an antisaccade task (AT), a number version of the Stroop task (NST), and a stop-signal task (SST) served as measures of inhibition. In the AT [1, 3–5], participants had to avoid automatic saccades toward a salient cue appearing on the computer screen. On every trial, a central fixation cross was presented, followed by a cue (black square) on the right or on the left side of the screen (50 % probability for each side). The time interval between the fixation cross and the cue was variable, with one of nine durations between 1500 and 3500 ms at intervals of 250 ms. After a fixed duration (183 ms in the prosaccade and the third antisaccade block, 200 ms in the second antisaccade block, and 233 ms in the first antisaccade block, see below), the cue disappeared and a target stimulus was displayed, showing a number between 1 and 9. The target either appeared on the same side as the cue (‘prosaccade’) or on the opposite side (‘antisaccade’). The target was masked after 150 ms by a black cross-hatching so that the participants would only be able to interpret the target if they executed the appropriate saccade (i.e., toward the cued side in prosaccade blocks and away from the cued side in antisaccade blocks). Participants indicated the number shown by the target by pressing the corresponding key on the number block of the keyboard, prioritizing accuracy over speed. To establish a prepotent response, the task began with a prosaccade block (18 trials, preceded by 12 practice trials). Then, participants completed three antisaccade blocks (36 trials each, preceded by 12 practice trials). Every block also contained two ‘warm-up trials’ that were discarded from the analyses. The outcome measure was the proportion of correct responses in antisaccade blocks.

The NST [1, 6–8] was modeled after the Stroop color-word interference task. In the number version, participants had to suppress the tendency to read out numbers from a string, but indicate its length instead. On every trial, participants saw a fixation cross (250 ms after a blank period of 750 ms), followed by a string of variable length (1-6 elements). The string remained on the screen until a response was made. Participants indicated the length of the string by pressing the corresponding key on the number block of the keyboard as fast and as accurately as possible. The task began with a ‘neutral’ block, where the strings consisted of asterisks (e.g., ‘* * *’, correct response is ‘3’) and did not induce response conflict (42 trials, preceded by 10 practice trials). Next, a block of 42 number strings was presented (preceded by 10 practices trials), where the length of the string corresponded to the displayed number (‘congruent’; e.g., ‘3 3 3’, correct response is ‘3’). Finally, two blocks of 42 ‘incongruent’ trials were presented, where the length of the string never corresponded to the displayed number (e.g., ‘4 4 4’, correct response is ‘3’). The outcome measure was the difference in median RTs (for correct responses) between incongruent and congruent trials.

In the SST [1, 4, 9, 10], participants needed to withhold the tendency to perform a simple categorization task, depending on the presence of a stop signal. On every trial, participants indicated whether a centrally presented green arrow pointed to the left (‘z’-key) or to the right (‘/’-key) as quickly and as accurately as possible (‘go trial’). However, responses should be withheld whenever the arrow turned red (‘stop trial’; 25 % of the trials). A staircase algorithm ensured that participants would be able to stop successfully on 50 % of the stop trials by adjusting the stop-signal delay (i.e., the time between the moment where a green arrow appears on the screen and the moment where this green arrow turns red). The initial stop-signal delay was set to 200 ms and increased or decreased by 50 ms, depending on whether the participant successfully withheld their response on the previous stop trial. The task began with 10 practice trials (only go trials) followed by a block of 50 go trials to establish a dominant response tendency. Next, it was explained that the following blocks would contain stop trials and that participants should try to withhold their responses when they saw the arrow turning red. It was stressed that slowing the responses should be avoided. After a block of 48 practice trials, participants completed three mixed blocks of 80 trials per block. The outcome measure was the stop-signal reaction time, defined as the difference between the median reaction time (RT) on go-trials (in mixed blocks) and the mean stop-signal delay (averaged across stop trials).

Shifting

Shifting was assessed using the category-switch task (CAST), the color-shape task (COST), and the number-letter task (NLT). In the CAST [1, 4, 11, 12], participants were required to switch between two tasks, the animacy task and the size task. On each trial, participants saw a target word on the screen (Dutch words for 'bee', 'butterfly', 'frog', 'goldfish', 'alligator', 'elephant', 'lion', 'shark', 'cigarette', 'key', 'pen', 'snowflake', 'house', 'piano', 'ship', 'table'). A visual cue, starting 350 ms before the target word, indicated which of the two tasks had to be applied (heart for animacy task, crossed arrows for size task). For the animacy task, participants indicated whether the word described a living or a non-living thing, by pressing the 'z'- or the '/'-key on the keyboard, respectively. For the size task, participants indicated whether the word described a thing that is smaller ('z'-key) or larger ('/'-key) than a football. Cue and target remained on the screen until a response was made. The next trial started 350 ms after the response. Errors were indicated by an auditory signal (200 ms). Participants first completed a block of 32 trials on the animacy task, followed by a block of 32 trials on the size task. Both single-task blocks were preceded by 12 practice trials, each, and included two 'warm-up trials' that were discarded from the analyses. Next, participants completed two blocks where both tasks were mixed in a pseudorandom manner (64 trials per block plus four 'warm-up trials', preceded by 24 practice trials). On 50 % of the trials, participants were required to repeat the task that they previously applied ('repeat trial'), whereas they needed to switch to the other task ('switch trial') on the remaining trials. The outcome measure was the difference in median RTs between switch and repeat trials in mixed blocks.

In the COST [1, 4, 7, 13], participants were required to switch between two tasks, the color task and the shape task. On each trial, participants saw a target on the screen (red circle, red triangle, green circle, green triangle). A visual cue, starting 350 ms before the target word, indicated which of the two tasks had to be applied (letter 'K' for color task ['color' = 'kleur' in Dutch], letter 'V' for shape task ['vorm']). For the color task, participants indicated whether the target was red ('z'-key) or green ('/'-key). For the shape task, participants indicated whether the target was a circle ('z'-key) or a triangle ('/'-key). Cue and target remained on the screen until a response was made and the next trial started 350 ms after the response. Errors were indicated by an auditory signal (200 ms). Participants first completed a block of 24 trials on the color task, followed by a block of 24 trials on the shape task. Both single-task blocks were preceded by 12 practice trials and included two 'warm-up trials' that were discarded from the analyses. Next, participants completed two blocks where both tasks were mixed in a pseudorandom manner (56 trials per block plus four 'warm-up trials', preceded by 24 practice trials). Half of the trials were repeat trials and the other half were switch trials. The outcome measure was the difference in median RTs between switch and repeat trials in mixed blocks.

In the NLT [1, 4, 14], participants were required to switch between two tasks, the number task and the letter task. On each trial, participants saw a target on the screen, being composed of a number (2-9) and a letter (A, E, I, U, G, K, M, R). These number-letter combinations were presented in one quadrant of a box, with the position indicating which of the two tasks needed to be applied. If the pair appeared in one of the two top quadrants, participants had to attend to the number and indicated whether it was odd ('z'-key) or even ('/'-key). If the pair appeared in one of the two lower quadrants, participants had to attend to the letter and indicated whether it was a consonant ('z'-key) or a vowel ('/'-key). 350 ms before the target was displayed, the respective quadrant darkened, representing a visual cue for the task to be performed. Cue and target remained on the screen until a response was made and the next trial started 350 ms after the response. Errors were indicated by an auditory signal (200 ms). Participants first completed a block of 32 trials on the number task, followed by a block of 32 trials on the letter task. Both single-task blocks were preceded by 12 practice trials and included two additional 'warm-up trials' that were discarded from the analyses. Next, participants completed two blocks where both tasks were mixed in a pseudorandom manner (64 trials per block plus four 'warm-up trials', preceded by 24 practice trials). Half of the trials were repeat trials and the other half were switch trials. The outcome measure was the difference in median RTs between switch and repeat trials in mixed blocks.

Updating

A digit-span task (DST), the keep track task (KTT), and a spatial 2-back task (STT) were used as measures of updating. The DST [7, 15] required participants to recall strings of numbers in forward or backward order, with increasing lengths. In the first part ('forward'), participants had to repeat the numbers in the same order as they appeared on the screen. In the second part ('backward'), participants had to repeat the numbers in the reverse order, starting with the most recent element. They responded by typing their answer on the number block of the keyboard, prioritizing accuracy over speed. Every trial started with a fixation cross (1000 ms), then a variable number of digits were shown one by one for 1000 ms each. In both conditions, the initial trial consisted of three digits. Then, trial length was increased by one digit after every two trials of the same length if the participant recalled at least one of the trials with the current length correctly. When a participant failed to repeat both strings, the block was terminated. The outcome measure was the total number of trials passed [15].

In the KTT [1, 4, 16], participants were asked to track up to five categories in a stream of words, recalling the last word presented for each of the categories at an unpredictable time. Each word belongs to one of six categories (animals [Dutch words for 'cat', 'dog', 'cow', 'horse', 'pig', 'sheep'], colors ['blue', 'green', 'grey', 'red', 'white', 'yellow'], countries ['England', 'France', 'Poland', 'Russia', 'Spain', 'Sweden'], fruit ['apple', 'banana', 'cherry', 'lemon', 'mango', 'melon'], metals ['cobalt', 'iron', 'tin', 'nickel', 'copper', 'zinc'], relatives ['mother', 'father', 'aunt', 'uncle', 'brother', 'sister']). On every trial, a number of target categories (2-5) was selected, and the category names were displayed at the bottom of the screen while 15-25 words (pseudo-randomly selected from all six categories) were shown to the participant for 2000 ms each. At the end of the trial, participants had to recall and type the most recent word for each target category. Two 2-category trials were given as practice trials, then 16 trials were administered, divided across four blocks, with each block containing one 2-, one 3-, one 4-, and one 5-category trial in random order. The outcome measure was the proportion of correctly recalled words across trials (unambiguously identifiable words with typing errors were counted as correct, where appropriate).

In the STT [1, 4, 17], participants were asked to judge whether a particular location on the screen had been highlighted two trials before the current one. Twelve white squares with black edges were presented on fixed locations distributed across a computer screen. In every block, every square was highlighted (i.e., turned black for 500 ms) twice, such that 24 of these 'flashes' occurred in a pseudorandom order. Flashes occurred one at a time, with 1500 ms between two flashes. For every flash, participants indicated whether the current square had been highlighted two trials before (by pressing the 'z'-key) or not ('/'-key). Errors (i.e., incorrect reactions or not reacting in time) were signaled by a 200 ms auditory signal. After a practice block of 20 flashes, participants completed six blocks (25 % 'yes'-responses per block). The outcome measure was the proportion of correct responses.

Motor task

Bimanual coordination was assessed using the bimanual tracking task (BTT [18]). Participants tracked a moving dot on a target line on the computer screen by bimanually rotating two dials at a prescribed frequency. Clockwise and counterclockwise rotations with the right hand caused the cursor to move to the right or left on the computer screen, respectively. Similarly, clockwise and counterclockwise rotations with the left hand caused the cursor to move upward or downward, respectively. In the 'straight' condition, the target trajectory was represented by a diagonal line (i.e., both dials should be rotated at the same speed in a constant direction). In the 'complex' condition, the target trajectory was represented by a zigzag line, with abrupt changes of direction [19, 20] (i.e., rotation direction in one hand should be maintained, whereas rotation direction of the other hand should be adjusted whenever the target dot changed its direction on the trajectory).

Participants were acquainted to the task in a first session (see General Procedure). Specifically, they were instructed on how to control the cursor by rotating the two dials. It was stressed that they should try to minimize the distance between cursor and target dot at all times. It was pointed out that both too slow and too fast movements would decrease the overall performance score, even when the trajectory was followed perfectly, because both too fast and too slow performance would result in increasing the distance between target and cursor. Then, participants practiced 16 simple 'straight' lines (four consecutive lines of each type). When they felt comfortable to proceed, the 'zigzag' lines were introduced. We explained that the zigzag trajectory would require one hand to perform changes in the rotational direction whereas the other hand was required to maintain its rotational direction. This was practiced on eight different zigzag lines (four horizontal, four vertical) with breaks in between. Each of these trials was repeated until the participant was comfortable to proceed to the next practice trial. In the end of the familiarization block, participants were asked to complete eight consecutive 'zigzag' lines (one of each type). This was followed by one last round of practicing, consisting of eight 'straight' (two consecutive of each type), four horizontal, and four vertical 'zigzag' lines (one consecutive of each type). At the end of the second testing session (see General Procedure), participants were re-acquainted to the task by completing eight 'straight' lines as well as two horizontal and two vertical 'zigzag' lines. Then, three blocks of BTT trials were administered, with short breaks in between: 1) 16 'straight' lines (four consecutive of each type), 2) 12 horizontal 'zigzag' lines (three consecutive of each type), and 3) 12 vertical 'zigzag' lines (three consecutive of each type).

The BTT was controlled by LabView 2016 (National Instruments, Austin, TX). Responses were recorded by sampling the cursor position at a rate of 100 Hz.

Every trial started with a display of the target trajectory on the computer screen ("planning phase", 4000 ms). The timing of the execution phase was invariant because of the fixed velocity of the target dot (15000 ms). Between two consecutive trials, there was a short break of 3000 ms.

Performance accuracy on the BTT was calculated as the percentage of coverage of the target line (i.e., 100 % coverage would imply perfect performance). Specifically, every sampled cursor position was considered to 'cover' the point on the target line with minimal Euclidian distance to the current cursor position. For every trial, the number of unique 'covered' points was divided by the total number of points on the target line and multiplied by 100 [19, 20]. This calculation results in a high accuracy score when the cursor is moved on or parallel to the target line at the same speed as the target dot. In contrast, the score decreases when the cursor is moved too fast or too slowly, when it is moved away from the target line or in the wrong direction, or when cutting corners in the 'zigzag' condition. To derive individual performance indices, accuracy scores were averaged across all 'straight' lines and across all 'zigzag' lines. The mean accuracy of zigzag lines was then used as an indicator of complex motor performance in the analyses.

General procedure

Testing was distributed across two days to prevent fatigue (Supplementary Figure 1). On test session 1, participants received general information before signing the informed consent. Before completing the first three neuropsychological tasks, they underwent MoCA (cognitive functioning) and PPVT (crystallized intelligence [21]) assessments and were administered the BSI-18 (psychological well-being). Participants were also asked to fill in questionnaires regarding lifestyle and medical history, handedness, physical activity, and health-related quality of life. At the end of this session, participants were familiarized with the BTT. Test session 2 comprised the last six neuropsychological tasks and the BTT. The order of the tasks was fixed to minimize between-subject variability in order to avoid such unspecific variance in the latent variable extraction [1]. On the first day, we administered the following neuropsychological tasks: (1) SST, (2) CAST, (3) DST. On the second day, we administered the remaining tasks: (4) COST, (5) KTT, (6) AT, (7) STT, (8) NST, (9) NLT. To ensure that any fatigue or learning effects would affect the three executive domains to a similar extent, the task order was built such that the sums of task-order positions were equal (i.e., 15) for inhibition, shifting, and updating tasks. To illustrate, the summed task-order position for inhibition tasks is 1 (position of SST) + 6 (AT) + 8 (NST) = 15. It was ensured that no two tasks from the same domain were directly following each other, and that tasks from all domains had been completed before another task from any given domain was administered again. In other words, all domains had to be covered n times before a task from any domain could have been administered for the n + 1-th time.

Data analysis

The neuropsychological data were processed in SPSS 26 (IBM, Armonk, NY) to derive the outcome measures (see Neuropsychological Tasks) [1]. BTT data were analyzed in Matlab 2019b (MathWorks, Natick, MA). Data analysis was performed in R 4.0.2 [22] in RStudio 1.3 (RStudio, Boston, MA), relying on the lavaan package version 0.6-7 [23] for structural equation modelling. The dataset and code are available on https://www.osf.io/5v2rz.

Processing of neuropsychological tasks

The RT-based outcome measures (NST, SST, CAST, COST, NLT) were calculated after excluding error trials and trials with premature responses (i.e., RT < 200 ms). For the shifting tasks (CAST, COST, NLT), trials following error trials were discarded, as it cannot be concluded with certainty whether those trials represent switch or repeat trials [1]. For NST, CAST, COST, and NLT, median RTs were extracted for every condition to calculate the desired outcome measure. For SST, the outcome measure was calculated as defined above. For AT, DST, KTT, and STT, outcomes were calculated based on the number (DST, KTT) or proportion (AT, STT) of correct responses.

Next, a pre-defined validity criterion was applied to every task to ensure that only those datasets were entered in the analyses where we had positive evidence that the individual was applying the task instructions. For the antisaccade task (AT), participants were excluded when their performance was indistinguishable from chance level in the prosaccade block. In other words, given that participants were administered 18 prosaccade trials and had a probability of 1/9 for responding correctly by arbitrarily pressing either response key (numbers 1-9), performance was significantly (p < .05) distinguishable from chance level when at least five correct responses occurred, as indicated by a binomial test. For the number-Stroop task (NST), participants were excluded when they failed to respond correctly on at least 12 trials in the neutral and the congruent condition, or on at least 21 trials in the incongruent condition (i.e., significantly better than 1/6 correct), as indicated by a binominal test. For the stop-signal task (SST), participants were excluded if they failed to respond correctly to at least 102 go-trials in the mixed blocks (i.e., significantly better than 50 % correct), as indicated by a binomial test. In addition, participants were excluded if they performed less than 24 and more than 36 stop-trials correctly. In other words, stopping accuracy had to fall between 40 % and 60 % to exclude that participants slowed their responses too much in the mixed blocks, but did not arbitrarily press either response key. For the category-switch task (CAST), participant were excluded when their task performance did not significantly differ from chance level. Binomial tests indicated that at least 22 trials needed to be correctly completed on single-task blocks, and that at least 40 trials needed to be correctly completed in both of the conditions (repeat, switch) in mixed blocks. The same criteria were used for the color-shape task (COST) and the number-letter task (NLT). Note that trial numbers on the COST differed slightly for counterbalancing reasons: participants had to complete at least 17 correct trials on single-task blocks and at least 35 correct trials in both conditions in mixed blocks in the COST. For the digit-span task (DST), participants were excluded when they failed to correctly complete one forward and one backward trial. For the keep track task (KTT), participants were excluded when they failed to recall all words correctly for at least one trial (regardless of the difficulty). For the spatial 2-back task (STT), participants were excluded when they failed to perform significantly above chance level across all blocks. A binomial test indicated that at least 83 trials had to be performed correctly. Supplementary Table 1 gives an overview of the datasets that were excluded as a result of individual-level validity checks. Taken together, only the stop-signal task mandated the exclusion of > 5 % of the sample. This is due to the especially strict criteria with regard to the correct stopping rate between 40 and 60 % that can only be achieved when response slowing in mixed blocks is avoided. After exclusion, 26 complete (i.e., validity criterion for all tasks passed) datasets from young adults and 92 datasets from older adults were retained for further analysis (see Supplementary Figure 2).

To minimize the influence of extreme scores, observations outside 3 *SD* from the respective group mean were replaced by the value at group mean plus (or minus) 3 *SD* [1]. This approach led to the replacement of nine individual values (0.85 % of the data). After this procedure, only the STT outcome in the young adults showed high kurtosis and was therefore arcsine transformed [1]. Measures based on RT were transformed such that higher scores indicated better performance for correlations and structural equation modeling.

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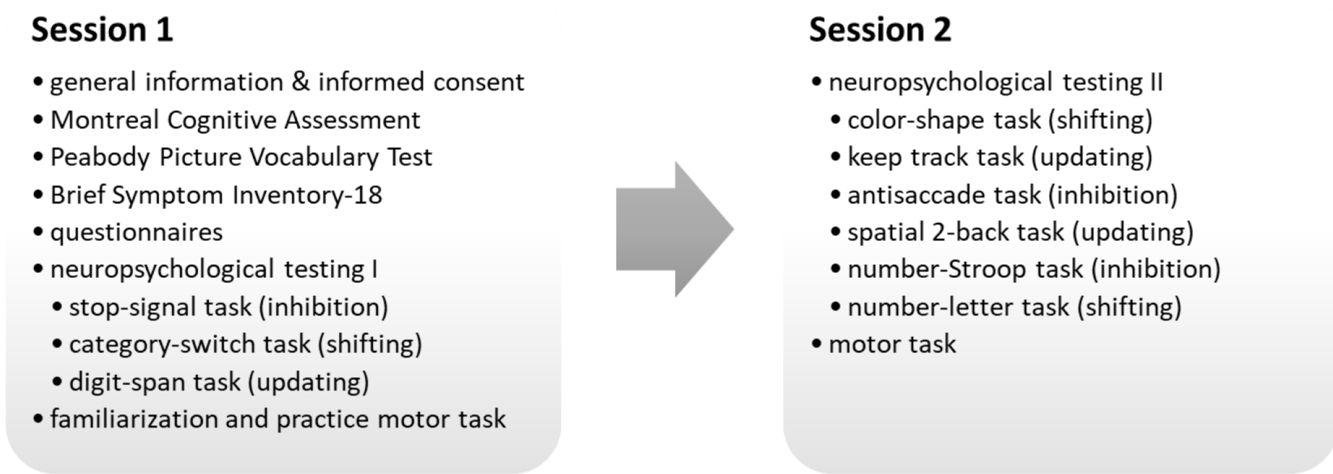
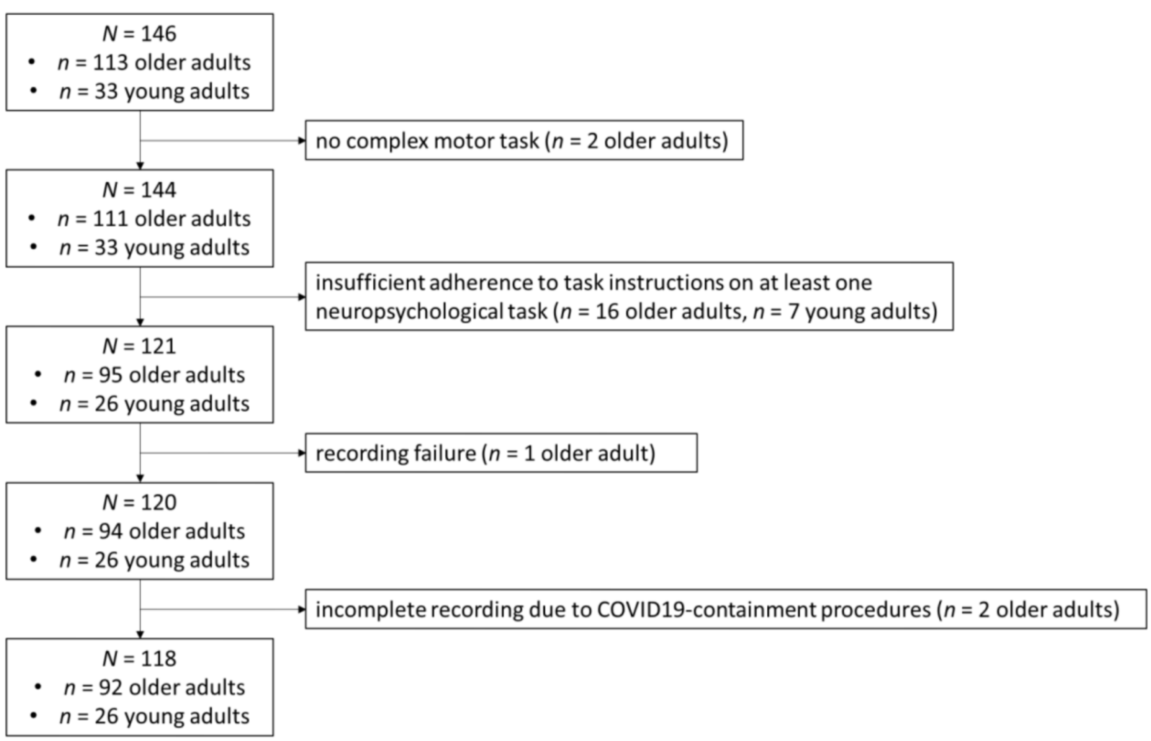
Supplementary Figures



Supplementary Figure 1. Description of the study protocol.



Supplementary Figure 2. Flow-chart describing the selection of the sample for the current analyses.

Supplementary Table

Supplementary Table 1. Datasets available for analysis after application of validity criteria.

Task	Group	*n* recorded	*n* (%) excluded	*n* available for analysis
Inhibition				
Antisaccade task	older adults	109	0 (0.00 %)	109
	young adults	33	0 (0.00 %)	33
Number-Stroop task	older adults	108	0 (0.00 %)	108
	young adults	33	0 (0.00 %)	33
Stop-signal task	older adults	110	7 (6.36 %)	103
	young adults	33	7 (21.21 %)	26
Shifting				
Category-switch task	older adults	111	1 (0.09 %)	110
	young adults	33	0 (0.00 %)	33
Color-shape task	older adults	109	4 (3.67 %)	105
	young adults	33	1 (3.03 %)	32
Number-letter task	older adults	108	2 (1.85 %)	106
	young adults	33	0 (0.00 %)	33
Updating				
Digit-span task	older adults	111	2 (1.80 %)	109
	young adults	33	0 (0.00 %)	33
Keep track task	older adults	109	0 (0.00 %)	109
	young adults	33	0 (0.00 %)	33
Spatial 2-back task	older adults	107	2 (1.87 %)	105
	young adults	33	0 (0.00 %)	33