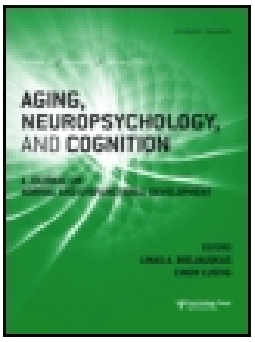

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Stroop switching card test: brief screening of executive functions across the lifespan

Maroua Belghali[a,b], Yauhen Statsenko[c] and Vasyl Laver[d]

[a]INSERM, COMETE, GIP CYCERON, Normandie Univ, UNICAEN, Caen, Research Unit: Aging, Health & Diseases, Caen, France; [b]College of Education, United Arab Emirates University, Al Ain, United Arab Emirates; [c]College of Medicine and Health Sciences, United Arab Emirates University, Al Ain, United Arab Emirates; [d]Department of Informative and Operating Systems and Technologies, Uzhhorod National University, Uzhhorod, Ukraine

ABSTRACT

This study aimed to: (1) propose a novel version of the Stroop switching test, namely the Stroop Switching Card Test (SSCT), to assess the overall efficiency of executive functions (EF) and its underlying cognitive processes (conflict resolution and conflict adaptation); (2) examine the utility of the SSCT in the assessment of EF in different age groups (age range 15-75 years), compare its results with standard neuropsychological tests (SNT), and (3) examine the contribution of both the processing speed and cognitive reserve on the performance of all used tests. The SSCT showed more sensitivity to detect subtle executive dysfunction in the middle age (~50 years). Going further, the SSCT revealed a progressive decline in conflict adaptation over two life periods. The first period of decline started at ~50 years and the second at~ 65 years. The processing speed and cognitive reserve had a prominent role in our results, notably in SSCT.

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aging; executive functions; processing speed; conflict resolution; conflict adaptation; Stroop Switching Test

Introduction

Brain aging is a complex process associated with progressive functional loss in many cognitive domains, including mental speed, episodic memory, and executive functions (EFs; Hoyer et al., 2004; Machado et al., 2012; Salthouse, 2017).

By focusing on EFs, there is an ongoing discussion on whether these cognitive functions are best described as a set of unique capabilities or whether they are merely reflective of a common process (Duncan, 2010; Martin et al., 2019; Stuss & Alexander, 2007). In general, authors argue that EFs are not just a reflection of information processing; the performance-based and rating measures of EFs assess different underlying mental constructs (M. Toplak et al., 2013). Typically, EFs are an umbrella term for a set of higher-order cognitive processes involved in a novel situation to organize intentional behavior (Miyake & Friedman, 2012). To put knowledge on EFs into a system, authors developed a considerable number of models. This is partly due to challenges in measuring the same EF abilities in different age groups. Based on a revised model, EFs comprise three skills, including (i) **inhibition**, (ii) **updating**, and (iii) **switching**, which can work either

CONTACT Maroua Belghali marouab@uaeu.ac.ae

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together or **separately** according to the cognitive demand of the task (Miyake & Friedman, 2012).

The EFs have elicited considerable interest, and their decline over the lifespan of an individual has become a major topic of research (Maldonado et al., 2020). To date, the majority of studies explored age-related EF changes with standard neuropsychological tests. The tests involve such EFs as inhibition (e.g., Stroop test, Flanker test, Simon test), updating (e.g., backward digit span test, n-back, letter-number sequencing task), and switching (e.g., trail making test, task-set switching). They provide an insight into how **the diversified nature** of EFs evolves or deteriorates with aging. Despite extensive research, the relationship between age and EFs is not fully understood. Some longitudinal and transversal studies revealed a significant decline from early adulthood into advanced age (Fine et al., 2008; Goh et al., 2013; Nilsson et al., 2012; Adólfsdóttir et al., 2016), whereas others did not (Salthouse, 1996; Verhaeghen, 2011; Verhaeghen & De Meersman, 1998; Zysset et al., 2007). Several reasons account for the discrepancies. Firstly, the authors used different methodology of testing. Secondly, some researchers did not consider the processing speed, i.e., "*how fast one can execute the mental operations needed to complete a task at hand*" (Salthouse et al., 2000). Finally, some authors did not control the cognitive reserve, which is the subject's background cognitive capacity influencing the task performance (Stern, 2009). Education is the most studied marker of cognitive reserve, notably because it might modify the relation of neuropathology on cognitive functions (Wilson et al., 2003). Meanwhile, all of these factors may either mask or exaggerate age-related decline in EFs. Moreover, these covariates should be controlled to provide evidence for specific age-related deterioration in EFs (Gilsoul et al., 2019; Maldonado et al., 2020).

The dualism (the unity and the diversity) of EFs provoked researchers to elaborate a new neuropsychological test that would assess inhibition and switching, concurrently; the Stroop Task Switching (STS), from the Delis-Kaplan Executive Function System (D-KEFS; Delis et al., 2001). The STS is a modified version of the classical STROOP test. It includes a switching condition in addition to the classic interference condition (i.e., *name the ink color that does not correspond to the meaning of the written word*). Specifically, subjects were instructed to read the conflicting words or name the incongruent ink of colors, depending on where the words are *printed*. The main argument of this innovation is that some authors justified the age effect of primary involvement of frontal lobe subareas on performance in EF tests of inhibition and switching (Adólfsdóttir, 2014). Clinically, this will help to reveal early executive decline that remains undetected with standard neuropsychological tests; hence, it could be meant to exhaust compensation strategies aimed at preserving the executive functioning when the prefrontal cortex is altered (Hutchison et al., 2010).

A longitudinal study of one year by Fine et al. (2008) supported this assumption. The authors showed that older adults whose executive functioning had declined over the year had a larger Switch Discrepancy Score (i.e., the difference between Stroop switch performance and average performance on classical Stroop) compared to those whose executive performance remained stable. Similarly, a study by Hutchison et al. (2010) comparing healthy older adults to individuals diagnosed with mild dementia has shown that the STS performance exceeded current psychometric tests in discriminating healthy aging from the early phase of Alzheimer's disease (AD). Notably, patients with an early AD produced larger Stroop interference and made more error rates than healthy older adults. A longitudinal study by Adólfsdóttir et al. (2016) showed a linear decline of executive functioning in middle-aged and older adults independently from the processing speed, gender, and education.

It is worth mentioning that any changes in the cognitive sequence will influence its underlying mental process. The Gratton theory suggests that the characteristics of a stimulus in the current trial influence the dynamic response in the next attempt. Specifically, responses are faster and more accurate when incongruent trials follow another incongruent trial (II; **conflict resolution)** rather than they occur after a congruent one (CI; **conflict adaptation)** (Aschenbrenner & Balota, 2015; Gratton et al., 1992; Kim et al., 2016). Furthermore, adding a cue in the cognitive sequence indicating how to perform each trial might have a facilitating role in the executive control, in particular by relieving the role of the working memory. In the STS, working memory is involved when participants are required to maintain multiple task sets while selecting the appropriate task set for the current trial (Hutchison et al., 2010).

Despite the relevance of these findings, some limitations reduce the benefits of STS. To date, various designs (e.g., paper or computerized) and sequences of the STS have been created making the comparison of results very difficult. For example, Fine et al. (2008) have used a single randomized condition including incongruent color words stimuli, whereas Hutchison et al. (2010) have used a range of them. Those were (i) neutral words (e.g., the word "bad" presented in green, blue or yellow), (ii) incongruent color words stimuli, and (iii) a cue indicating how to perform each trial. In a latter study, Rogers and Monsell (1995) presented a set of incentives in an alternating runs fashion (e.g., AA BB AA BB). With this design, the participant switches the response from one dimension (color or word) to another every two trials.

Another critical point to mention is that the majority of authors assessed only the overall time to complete the entire block of trials without considering the total number of errors and trial-specific switching effect (Hutchison et al., 2010). Adjustment for such covariates is crucial since the efficiency of STS depends on both the ability and speed of the brain to process information. Although Hutchison et al.'s (2010) study worked on these dependent variables, it did not however take into account inter-individual differences in processing speed and cognitive reserve.

Considering all the above limits, the objectives of our study were threefold. (i) To modify STS in the way, that it would assess the overall efficiency of EFs and its underlying cognitive process (e.g., the conflict resolution, the conflict adaptation). The novel test got the name Stroop Switching Card Test (SSCT). (ii) To examine the utility of the SSCT in the assessment of EFs in different age groups and to validate it by comparing test results with the standard neuropsychological tests. Those were the Stroop Test, Trail Making Test, and Digit span Forward and Backward Test. (iii) To estimate the role of the processing speed and cognitive reserve on age-related changes of EFs assessed with the standard neuropsychological tests and the novel one.

Table 1. Mean (standard deviation) of demographic characteristics of participants.

	Adolescents	Young adults	Midlife adults	Older adults
Gender				
Female	52%	52%	48,1%	42,3%
Male	48%	48%	51,9%	57,7%
Age (years)	17.40	26.40	50.25	67
	(1.29)	(4.30)	(5.15)	(4.55)
Education (years)	12.45	15.70	9.25	8.16
	(1.21)	(2.87)	(5)	(5.39)

Material and methods

Participants

A sample of 103 participants, aging from 15 to 75 years, participated voluntarily in this experiment. The study sample was divided into 4 groups: adolescents (n = 25; 15–19 years), young adults (n = 25; 20–39 years), midlife adults (n = 27; 40–59 years) and older adults (n = 26; 60–79 years). The demographic characteristics of the participants are in Table 1. The inclusion criteria were: (i) literate, (ii) a score of Mini-Mental State Examination greater or equal to 27, and (iii) the absence of visual and auditory impairments. The exclusion criterion was the presence of any medical, psychiatric, or neurologic impairment that could significantly affect cognitive functions. The written informed consent was obtained from each participant.

Protocol overview

The experiment took place in the participant's residence in the quietest workspace. In randomized order, each participant completed a battery of widely used tests designed to assess: (i) inhibition, i.e., the Stroop Test (Golden, 1978; Stroop, 1935), (ii) switching (i.e., Trail Making Test; Reitan, 1958), (iii) updating (i.e., Digit Span Forward and Backward test; Wechsler, 1997), and (iv) processing speed (i.e., Digit Symbol Substitution Test; Wechsler, 1997), and the SSCT by Dr. Maroua Belghali. Each participant was tested individually in a single session lasting about one hour. The total number of years of education served as an indicator of cognitive reserve.

The protocol of the study was approved by the CERSTAPS (Ethical Committee of Sport and Physical Activities Research), Notice Number: 2016–26-04-13.

Standard neuropsychological tests

Stroop test

The test assessed inhibition and included two basic conditions of color naming (STROOP A) and word reading (STROOP B) and the third condition in which individuals must name the ink color that did not correspond to the meaning of the written word (STROOP C). We recorded the completion time of STROOP A, STROOP B, and STROOP C. The interference score (IS) was the dependent variable calculated as below:

$$IS = STROOP\ C - [(STROOP\ A + STROOP\ B)/2]$$

Trail making test (TMT)

The test assessed switching and included two conditions: Part A, requiring the serial connection of the numbers 1 through 25 (1–2–3 ...), and Part B, requiring serial alternation between number and letter sequences (1 – A–2–B–3 ...). We collected the completion time for Part A and B. The switch score (SS) was the dependent variable calculated as below:

$$SS = TMT\ B - TMT\ A$$

Digit span forward and backward test

The test assessed updating and included two sequences. During the Forward sequence, the participant must repeat in direct order digits given by the experimenter. In the Backward sequence, the individual must repeat the numbers in the inverse order. There were two trials for each list length. The examinee started with two digits until reaching nine digits for the Forward sequence, and eight digits for the Backward set. The dependent variable of interest was the total number of lists reported correctly in both series, and it referred to the Wechsler total score.

Digit symbol substitution test

The test assessed the processing speed. It consisted of a key grid of nine numbers and matching symbols, and a test section with symbols and empty boxes. The subject was asked to write down the corresponding characters under the numbers as fast as possible. The total number of correct symbols within the allowed time (i.e., 90 sec) was the dependent variable of interest.

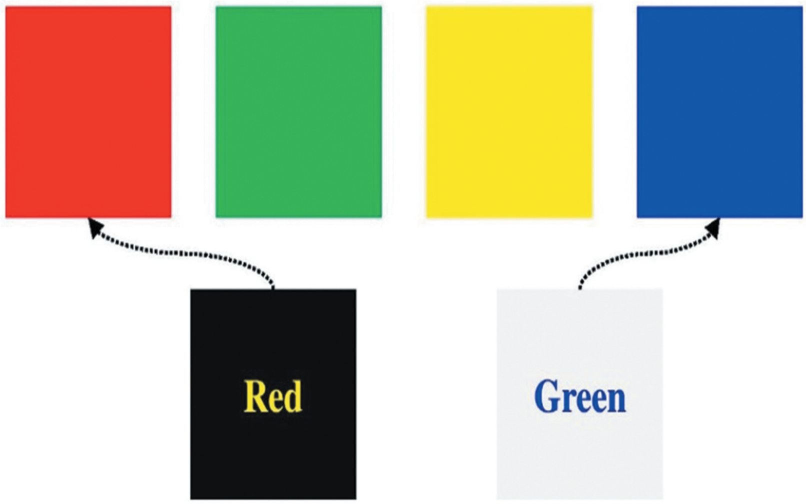
Stroop switching card test

Description

Four cards that differ only in color (i.e., red, blue, green, or yellow) were placed in front of the participant. The examinee held 36 colored cards with either black or gray background each one. The instruction was to check the background of each card one by one. In case it was gray, the participant was to say aloud the ink color of the written word as quickly as possible. If the background was black, the examinee should pronounce the written word. Finally, the cards must be classified into four groups depending on the color named (Figure 1).

Stimuli

The stimuli consisted of four-colored words (red, blue, yellow and green) presented either in the color corresponding to the colored word for four stimuli (congruent) or each of the three incongruent colors (e.g., the term "red" presented in green, blue, or yellow). The sequence contained 36 stimuli, half of them were congruent (e.g., RED), another half were incongruent (e.g., RED). The combination of incentives was designed in a way to monitor information processing while assessing either inhibition or inhibition and switching with six sequences (Figure 2(a,b) and without the involvement of the cognitive control in the other four rows (Figure 2(c)).



Specific instruction: "I will give you a deck of cards. You have to say, as quickly as possible and without making errors either the color of the ink of the written word when the background of the card is gray or the written word when the background of the card is black. Depending on your answer, you have to place your card on the corresponding color. If you make a mistake, don't stop the test, don't stress, don't talk to me and keep doing your best. Do you have any questions? Are you ready? "

Figure 1. Stroop Switching Card Test.

Dependent variables of the Stroop Switching Card Test

We created two types of dependent variables: global and specific ones. The *global dependent variables* reflected the overall efficiency of EF. These were the global response time (SSCT_TIME) to complete the SSCT, and the total number of response errors (SSCT_ERROR). The *specific dependent variables* of interests described exact EF domains, i.e., the inhibition, the inhibition with switching. These were the numbers of errors done while performing each sequence assessing inhibition, and inhibition and switching, simultaneously. Out of them, we calculated metrics of both conflict resolution and conflict adaptation.

The conflict resolution referred to the ability to select the relevant information while suppressing the distracting information irrelevant to the running task. The response error difference between the congruent and incongruent trials reflected the conflict resolution (Puccioni & Vallesi, 2012). There were two ways to apply the concept to a cognitive sequence of the SSCT without changing the stimuli congruence. The first way was by involving just **the inhibition** either by naming an incongruent ink color preceded by an incongruent ink color or by reading an incongruent color-word preceded by an incongruent color-word. It was "Inhibition conflict resolution" (see diagrams on the left side of Figure 2(a)). The second way was by involving **the inhibition and switching**, i.e., switching between naming the incongruent ink of colors and reading the words or vice-versa. It was "Inhibition and switching_conflict resolution" (see Figure 2(b)).

The conflict adaptation referred to the ability to adjust the response to the congruence changes of the successive trials. In the SSCT, the conflict adaptation could be applied in

Figure 2. Specific dependent variables of the Stroop Switching Card Test and related cognitive processes.

the cognitive sequence involving inhibition with a congruence change(e.g., naming an incongruent ink color preceded by a congruent ink color). The measure of the conflict adaptation was the response error difference between the congruent trial following the incongruent one and the incongruent trial following another incongruent one (Puccioni & Vallesi, 2012). See the diagrams on the right side of Figure 2(a).

Statistical analysis

For the statistical analyses, IBM SPSS 21.0 was used. Alpha was set at 0.05 for all analyses. Basic assumptions were checked, and outliers with a score of >3 SD were removed. First, the correlations between age, cognitive reserve (total number of years of education), and all dependent variables were checked using Pearson correlation coefficients. Second, we computed a regression analysis to investigate age effects on EF. IS (inhibition), SS (switching), the Wechsler total score (updating) served as the dependent measures for the standard neuropsychological tests. SSCT_TIME, SSCT_ERROR, SSCT_inhibition (conflict adaptation) SSCT_inhibition (conflict resolution), and SSCT_inhibition and switching (conflict resolution), served as the dependent measures for the SSCT. We performed a hierarchical regression analysis to examine whether non-executive measures could account for age variability in all dependent measures. In the first step, age was included as a predictor. In the second step, processing speed and the total number of years of education were included as predictors. For measuring the differences between age groups, we used the Kruskal-Wallis rank-sum test. Post-hoc comparisons were performed with Dunn corrections for multiple comparisons.

Results

Correlation analysis

Figure 3 shows the correlation matrix between age, cognitive reserve (education), processing speed, and SSCT measures. Figure 4 shows the correlation matrix between age, cognitive reserve (education), processing speed, and all standard neuropsychological tests. All correlations were statistically significant ($p < 0.05$). Blue color shows a positive correlation, and the pink color stands for the negative one.

Effect of age on processing speed and executive functions as assessed by standard neuropsychological tests

Hierarchical regression analysis

In the first step, age accounted for approximately 48% of variability in inhibition $F(1, 102) = 30.77$, $p < 0.0001$, 19% of variability in switching, $F(1, 102) = 24.63$, $p < 0.0001$, and 12% of variability in updating $F(1, 102) = 14.37$, $p < 0.0001$. The inclusion of processing speed and education as predictors in the second step increased the explained variability to 21% and 30% in switching $F(3, 102) = 8.99$, $p < 0.0001$, and updating $F(3, 102) = 14.53$, $p < 0.0001$, respectively. However, the explained variability decreased to 24% in inhibition $F(3, 102) = 10.71$, $p < 0.0001$. The explained variability in inhibition and switching was largely accounted for age. The contribution of both speed and education failed to reach significance in both. For updating, speed was the only significant predictor. Age was no longer significant, Table 2.

Kruskal-Wallis rank-sum test

Results revealed reliable age differences in the expected direction (i.e., age decline) in all cognitive variables, which of course merely represents the abovementioned age difference, with all $p <.001$. Mean scores of processing speed and updating decreased significantly and to the same extent, in midlife adults and older adults compared to young adults. Mean scores of SS and IS markedly increased in older adults by comparison with young adults, but not with midlife adults. No significant difference was observed between adolescents and young adults in all dependent variables, Table 3.

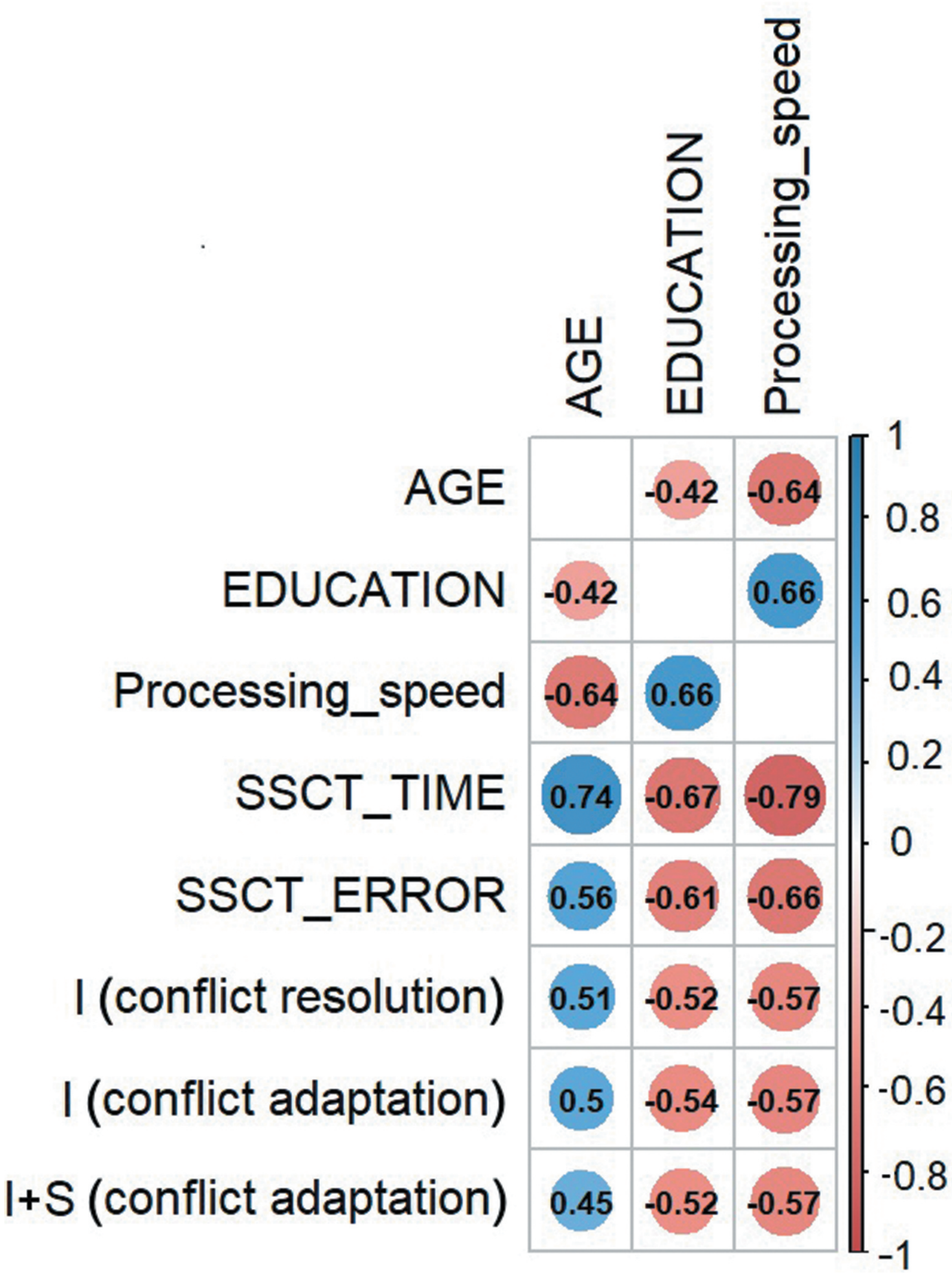


Figure 3. Correlation matrix between age, cognitive reserve (education), processing speed, and SSCT measures. The blue color shows a positive correlation, pink color stands for the negative one. SSCT_TIME = Global response timeSSCT_ERROR = Total number of response errors.I = inhibition I + S = inhibition and switching.

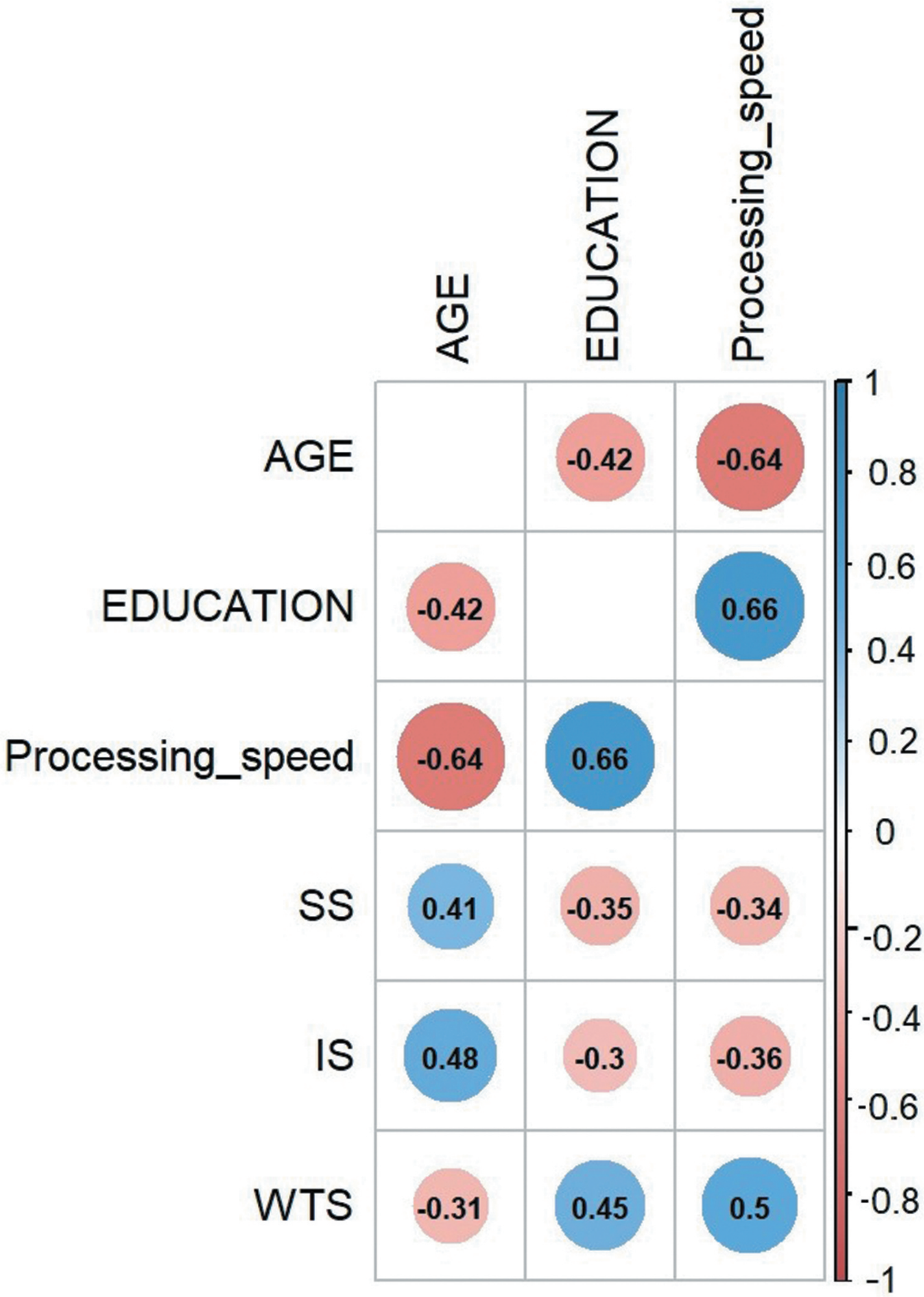


Figure 4. Correlation matrix between age, cognitive reserve (education), processing speed, and all standard neuropsychological tests. The blue color shows a positive correlation, pink color stands for the negative one. IS = Interference score (inhibition)SS = Switch score (switching)WTS = Wechsler total score (updating).

Table 2. Hierarchical regression predicting executive function performance.

	Age		Age ×	Speed ×	Education	
Model	β	R^2	β	β	β	R^2
Inhibition	.23***	.48	.42***	−.01	−.12	.24
Switching	.44***	.19	.39***	.06	−.17	.21
Updating	−.35***	.12	.05	3.50***	1.35	.30
SSCT$_{_TIME}$	.68***	.46	.30***	−.42***	−.20**	.66
SSCT$_{_ERROR}$	.59***	.35	.26***	−.29***	−.29**	.52
Inhibition (CR)	.54	.28	.28**	−.20	−.26*	.39
Inhibition (CA)	.53***	.28	.25*	−.19	−.31***	.41
Inhibition and switching (CR)	.47	.21	.15	−.31*	−.23*	.35

CR (conflict resolution); **CA** (conflict adaptation);***p <.001; **p <.01; *p <.05.

Effect of age on processing speed and executive function as assessed by the Stroop Switching Card Test

Hierarchical regression analysis

Global dependent variables

In the first step, age accounted for approximately 46% of variability in SSCT_TIME, F (1, 102) = 88.03, p < 0.0001, and 35% of variability in SSCR_ERROR, F (1, 102) = 54.34, p < 0.0001. Inclusion of processing speed and education as predictors in the second step increased the explained variability to 66%, F (3, 102) = 89.96, p < .0001, and 52%, F (3, 102) = 36.49, p < 0.0001 in SSCT_TIME and SSCT_ERROR, respectively. All global dependent variables were largely accounted for by processing speed. The contribution of age and the cognitive reserve was also significant, Table 2.

Specific dependent variables

In the first step, age accounted for approximately 28% of variability in both inhibition (conflict resolution), F (1, 102) = 42.39, p < 0.0001, and inhibition (conflict adaptation), F (1, 102) = 40.68, p < 0.0001, and 21% of variability in inhibition and switching (conflict resolution), F (1, 102) = 28.84, p < 0.0001. Inclusion of processing speed and education as predictors in the second step increased the explained variability to 39%, 41% and 35% in inhibition (conflict resolution) F (3, 102) = 23.18, p < 0.0001, inhibition (conflict adaptation), F (3, 102) = 24.87, p < 0.0001 and inhibition with switching (conflict resolution), F (3, 102) = 19.54, p < 0.0001, respectively. The inhibition (conflict resolution), and inhibition (conflict adaptation) were largely accounted for age and education. The contribution of processing speed failed to reach significance in both. For the inhibition and switching (conflict resolution), the significant predictors were processing speed and education. Age was no longer significant, Table 2.

Kruskal-Wallis rank-sum test

Global dependent variables

Results revealed reliable age differences in the expected direction (i.e., age decline) in all cognitive variables with all p < 0.01. Dunn post hoc analysis showed that mean scores of SSCT_TIME increased significantly, and to the same extent, in midlife adults and older adults compared to young adults. SSCT_ERROR increased significantly only in older adults

Table 3. Participants' mean scores and standard deviations on the neuropsychological tests as a function of age group.

Cognitive domain	DV	AD	YA	MA	OA	H value	ES	AD > YA	YA > MA	YA > OA	MA > OA
Processing speed	TCS	52.88 (9.12)	52.72 (10.95)	34.75 (12.27)	33.12 (11.14)	46.54	0.456	P = 1	P = 0.0001	P = 0.0001	P = 0.995
Switching	SS	45.24 (16.70)	40.76 (16.63	61.56 (37.11)	77.04 (38.10)	19.64	0.192	P = 0.995	P = 0.083	P = 0.0001	P = 0.165
Inhibition	IS	29.30 (16.41)	30.42 (29.31)	53.48 (21.93)	62.48 (19.93)	27.98	0.249	P = 0.320	P = 0.136	P = 0.003	P = 0.620
Updating	WTS	18.64 (3.05)	20.80 (4.41)	16.19 (3.14)	16.54 (3.56)	19.62	0.192	P = 0.190	P = 0.0001	P = 0.001	P = 0.982
Global executive functioning efficiency	SSCT_TIME	84.24 (22,86)	82.2 (22.44)	177.925 (65.53)	221.423 (99.94)	70.36	0.689	P = 1	P = 0.0001	P = 0.0001	P = 1
	SSCT_ERROR	1.32 (1.51)	1.88 (2.61)	3.92 (3.31)	6.80 (4.31)	30.08	0.294	P = 1	P = 0.302	P = 0.0001	P = 0.047
Inhibition (CR)	TNE	.52 (.77)	.96 (1.48)	1.67 (1.66)	3.24 (2.27)	23.33	0.228	P = 1	P = 0.817	P = 0.001	P = 0.112
Inhibition (CA)		.36 (.56)	.20 (.40)	.64 (.68)	1.44 (.76)	32.66	0.320	P = 1	P = 0.043	P = 0.0001	P = 0.004
Inhibition and switching (CR)		.40 (.64)	.60 (.91)	.92 (.97)	1.72 (1.20)	19.25	0.188	P = 1	P = 1	P = 0.004	P = 0.138

H value: referred to Kruskal Wallist test; ES referred to the effect size = H/(N-1); DV: dependent variable; CR (conflict resolution); CA (conflict adaptation); TCS: total number of correct symbols; SS: (TMTB-TMTA); IS [STROOP C-(STROOPA + STROOP B)/2]; WTS: Wechsler total score; AD: adolescents; YA: young adults; MA: midlife adults; OD: older adults.

compared to both young adults and midlife adults. No significant difference was observed between adolescents and young adults in all dependent variables, Table 3.

Specific dependent variables

Results revealed reliable age differences in the expected direction (i.e., age decline) in all cognitive variables. Dunn post hoc analysis showed that the total number of response errors in (i) Inhibition without a congruence change (conflict resolution), and (ii) inhibition and switching (conflict resolution) increased significantly only in older adults by comparison with the remaining groups. The total number of response errors in inhibition with a congruence change (conflict adaptation) increased significantly only in older adults compared to both young adults and midlife adults. Interestingly, a significant difference was also observed between midlife adults and young adults. No significant difference was observed between adolescents and young adults in all dependent variables, Table 3.

Discussion

The goal of this study was multifaceted. First, we proposed a new elaborated version of the Stroop switching test, namely the SSCT by Dr. Maroua Belghali. The SSCT assessed the overall efficiency of EFs, and its underlying cognitive processes (conflict resolution and conflict adaptation). The idea of it arose from the legitimate argument that a single brief executive assessment tool cannot itself be sufficient to reveal early executive decline. Second, we examined the utility of the SSCT in the assessment of EF in different age groups and compared its results with standard neuropsychological tests widely used to assess inhibition (Stroop Test), switching (Trail Making Test), and updating (Digit Span Forward and Backward test). Finally, we evaluated the contribution of processing speed and cognitive reserve on the performance of all used tests.

Effect of age on processing speed and executive function as assessed by standard neuropsychological tests

Aging affected the processing speed and all components of EF, significantly. A differential effect of age was also found in that the processing speed and updating were affected earlier (40–59 years) than other EFs' components (i.e., inhibition and switching: 60–79 years). A decrease in processing speed has been previously shown in earlier studies (see Hoyer et al., 2004, for a meta-analysis; Ferreira et al., 2015) and it was thought to result from a diffuse or global deterioration of white matter integrity throughout the brain (Albinet et al., 2012; Kerchner et al., 2012). Early decline in updating also supported previous studies (e.g., Kumar & Priyadarshi, 2013) and was thought to result from changes in the prefrontal cortex, and a decrease in processing speed (Salthouse, 1996). The results of our study are in favor of an age-related slowing in processing speed.

In contrast with the updating component affected earlier, the declines in both switching and inhibition were originating in our study at an older age (60–79 years). Furthermore, switching and inhibition declined independently of age-related slowing in processing speed and the protective cognitive reserve. Thus, the "frontal lobe hypothesis" (West, 1996) was the safest assumption explaining age-related declines in inhibition and switching. The "frontal-lobe hypothesis" proposed that the cognitive processes supported by the prefrontal cortex are particularly vulnerable to normal aging, and would manifest decline in greater magnitude than would cognitive processes requiring non-frontal regions (Dempster, 1992; Hartley, 1993; Moscovitch & Winocur,). Age-related decreases in inhibition and switching replicated and extended previous studies comparing efficiency in inhibition and switching between young adults and older adults (Ferreira et al., 2015; Hashimoto et al., 2006; Mutter et al., 2005).

Interestingly, midlife adults had performance closer to young adults rather than to older ones. The findings lead to the suggestion that the midlife period (40–59 years) is the transition period of changes in EF, in which some people perform, better than others. Some midlife adults were already cognitively old at midlife, whereas others were indistinguishable from young adults. Our view is in line with the moderating role of cognitive reserve (Stern, 2009). The latter posits that those with a high cognitive reserve display better executive performance than those with low cognitive reserve, despite an equivalent level of frontal brain damages (Cabeza et al., 2019; Machado et al., 2012; Stern, 2012; Salthouse, 2017).

Effect of age on executive function as assessed by the Stroop Switching Card Test

Aging affected the overall efficiency of EF significantly. Specifically, the SSCT_TIME increased significantly, and to the same extent in midlife adults and older adults compared to young adults. The SSCT_ERROR increased significantly only in older adults compared to both young adults and midlife adults. Regression analysis showed that the theories of "processing speed", "cognitive reserve and "frontal-lobe" might explain our results, and none of them can be considered as the sole contributor (Albinet et al., 2012; Schretlen et al., 2000). We suggest that the overall efficiency of EF begins to decline at ~50 years and becomes deficient at ~ 65 years, Figure 5. From our point of view, a decline means a decrease in the efficiency where participants are slower but not less accurate than young adults (i.e., which is the case of midlife adults), while a deficit means an impairment where participants are both slower and less accurate than young adults (i.e., which is the case of older adults), Table 3. It is worth mentioning that deficit in EF begins even before the diagnosis of numerous neurodegenerative diseases such as Alzheimer's disease (Hutchison et al., 2010). Given the importance of our results, future studies, including a large sample size with a broad diversity of life experiences, will be needed to propose a threshold of SSCT changes associated with different types of aging.

Aging affected inhibition (conflict adaptation), significantly. Specifically, the total number of response errors in CI trials increased significantly in older adults compared to both young adults and midlife adults. More interestingly, midlife adults made more errors compared to young adults and made fewer errors compared to older adults. Mechanistically, the fact that the total number of errors increased independently from processing speed constitutes strong and consistent support for an age-related decline in conflict-adaptation. Hence, this finding supports the frontal lobe damage hypothesis and is in line with previous studies showing a decline in inhibition requiring a conflict adaptation (Larson et al., 2016; Mutter et al., 2005).

Furthermore, our study suggests progressive retardation in conflict adaptation over two life periods. The first period of decline started at ~50 years and the second at~

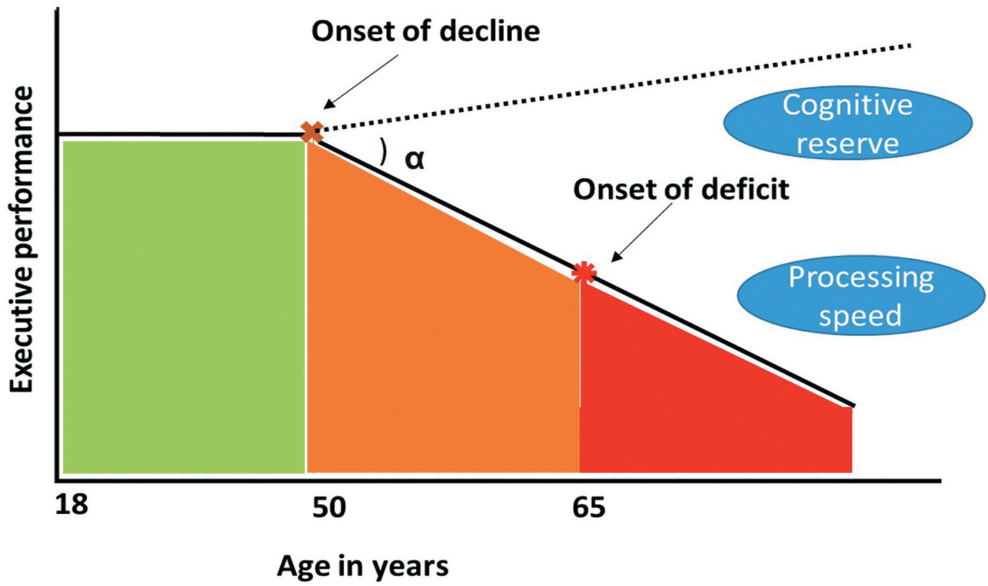


Figure 5. Theoretical illustration of age-related changes in the overall efficiency of executive functions. The overall efficiency of EF might start to decline at ~50 years (orange zone) and might become deficient at ~ 65 years (red zone), comparing to young adults (green zone). The processing speed and cognitive reserve may mediate the relationship between age and the overall efficiency of executive functions. The dotted line and the angle ? Referred to the effect size of the processing speed and cognitive reserve; the more we grow, the grater is the effect.

65 years. Clinically, this measure could be particularly relevant for future studies to distinguish healthy EF aging from the pathological one, notably because it may measure frontal brain damages. Neuroimaging studies are needed to confirm this view. The cognitive reserve was strongly correlated with conflict adaptation. This finding provides further support for its moderating role in executive decline (Botvinick et al., 2001; Lavrencic et al., 2018; Roldán-Tapia et al., 2012; Stern, 2009).

Aging affected the inhibition (conflict resolution), significantly. Specifically, the total number of response errors increased significantly in older adults by comparison with young adults but not with midlife adults, and this independently from the effect of processing speed. These results confirmed previous findings showing age-related differences in conflict resolution (Ikier et al., 2008; Puccioni & Vallesi, 2012). The fact that the cognitive reserve was associated with the total number of response errors suggests that older adults can cope better with age-related impairment in inhibition (conflict resolution) if they have a higher level of education.

Aging affected the inhibition and switching (conflict resolution), significantly. The total number of response errors increased significantly in older adults by comparison with young adults but not with midlife adults. These results were best explained by combining theories of processing speed (e.g., Salthouse, 1996) and cognitive reserve (Stern, 2009). To our knowledge, only one study has assessed inhibition (conflict resolution) and switching together (Hutchison et al., 2010). The authors have shown that young adults and older adults decreased their cognitive performance to the same extent (switch cost based on response time). A possible explanation of this contradictive finding is that the authors used a cue indicating how to perform each trial, while in our study, no cue was used. We suggest that adding a hint may decrease the cognitive load of the task, thereby minimizing the possibility of capturing changes in cognitive control associated with aging.

Stroop switching card test versus standard neuropsychological test

All measures of the SSCT were strongly correlated with the (i) IS, (ii) SS and (iii) WTS measures, thus confirming that the STSS tapped into the three components of EF, simultaneously. From the comparison of the SSCT with the standard neuropsychological tests, there is clear evidence that our test is more sensitive to age. This can be argued in two different ways. First, the SSCT_TIME detected subtle executive dysfunction more sensitively in the middle-aged cohort with the largest effect size (0.68), which is not the case of both the IS and SS (**see** Table 3). A possible explanation is that the SSCT required higher implication of the EF and/or cortical-subcortical frontal connections, in comparison with both the STROOP and TMT tests.

When performing cognitive control tasks, older adults show different functional activation patterns than younger adults in the prefrontal cortex. Some of these age-related changes are associated with better task performance (e.g., compensatory response), which reduces the informative value of the test (Maldonado et al., 2020). A supposed way to increase the sensitivity EF tests is to assess the overall efficiency of EF because this strategy exhausts the compensatory response. Our results support this idea.

A further argument is that only the SSCT revealed a progressive decline in conflict adaptation throughout two life periods (middle age and old age). Clinically, this finding, together with future research, may be necessary for the diagnosis, prognosis, and prevention of pathological aging at a very early level.

Interestingly, SSCT_ERROR, IS, and SS demonstrated similar results. The facts suggest that the TMT and STROOP tests can track changes in EFs only at old age, where EFs are already deficient.

Strengths and limitations

To our knowledge, this was the first study proposing a new neuropsychological test assessing the overall efficiency of EF and its underlying cognitive processes, simultaneously. The main strengths were the task design, choice of dependent variables, and the use of a statistical procedure allowing adjustment for processing speed and a potential marker of cognitive reserve (total number of years of education). This study has essentially three limitations. The first limitation was that the attentional capacities of participants were not considered. However, such kind of cognitive resource was crucial to perform the SSCT. The second limit was the small sample size of each group. Furthermore, the groups of midlife adults and older adults had lower numbers of total years of education, thus limiting the generalization of our results. Including a large representative, samples might benefit from proposing a threshold of EF changes related to the different types of aging. The third limitation is the absence of neuroimaging measures that support the results obtained in the applied neuropsychological measures. Methodologically, beyond processing speed effect, motor speed could also influence SSCT performance. To control this external factor, it would be interesting to use the Finger-Tapping Test (Strauss et al., 2006).

Conclusion

The SSCT was more sensitive to aging than the Stroop test and TMT test. Future neuroimaging studies, including a large sample size with a broad diversity of life experiences, are needed to propose a threshold of EF changes associated with different types of aging.

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Disclosure statement

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ORCID

Yauhen Statsenko http://orcid.org/0000-0002-7713-3333

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