The Role of Processing Speed, Flexibility, Productivity and Cognitive Control for Visual Learning Among Older Adults with Hypertension: A Study Into the Effects of Age and Education

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ABSTRACT

The current study aimed to assess the effect of age and education on executive functions and visual learning in older adults with hypertension. Further, the contribution of executive functions to visual learning was investigated at different stages of aging. Color Trails Test, Ruff Figural Fluency Test, and Visual Learning and Memory Test for Neuropsychological Assessment were used. A two-way analysis of covariance (ANCOVA) revealed main effects of age and education on executive functions and visual learning. A linear regression confirmed the contribution of cognitive flexibility to visual learning in groups aged 51-60 and 71-80. In the 61-70 and 71-80 groups, visual learning appeared dependent on productivity. Specific relationships were found between executive functions and the errors in visual learning. Our study confirms the need of using complex visual learning tasks as a measure sensitive to age-related changes and unveils the greatest impact of executive functions on visual learning in individuals aged 71-80.

KEYWORDS

cognitive aging
cognitive flexibility
processing speed
figural fluency
visual memory

INTRODUCTION

Executive functions are treated as cognitive capacities enabling goal-directed behavior and facilitating adaptation to environmental changes. Clinical neuropsychology promotes Lezak et al.'s (2012) approach, according to which executive functions are conceptualized as having the following components: goal formation, planning, realizing goal-directed plans, and effective performance. Purposeful and productive activity requires the capacities to initiate, maintain, switch, and stop the actions as needed. In spite of the apparent uncertainty concerning the exact nature of executive functions, it is generally accepted that executive functions are higher-level ones that integrate and control more basic cognitive processes (Baudouin et al., 2009; Diamond, 2013; Jodzio, 2008; Miyake & Friedman 2013; Taconnat et al., 2009). Lezak et al. (2012) suggested that as long as executive skills are preserved, a person can keep independence and efficiency of action despite the symptoms of cognitive loss in other domains.

Executive function abilities continue to change across the lifespan. Some studies particularly highlight the relevance of cognitive control (Borella et al., 2008; Ferguson et al., 2021) and processing speed (Brookes et al., 2013; Brown et al., 2012) for understanding of changes occurring with aging. Cognitive flexibility, considered in terms of ability to switch attention between tasks or mental sets, allows to adaptively maintain and manipulate information. Earlier studies revealed that poorer cognitive flexibility is the main component of cognitive aging associated with worse adapting to age-related changes (Blaskewicz Boron et al., 2018; Bouazzaoui et al., 2014; Ferguson et al., 2021; Richard's et al., 2021). Deterioration of older adults' executive functioning is also reported in the domain of figural fluency, which is regarded as an ability to utilize one or more strategies to generate nonverbal responses to a specific instruction, within limited time, while avoiding response repetition (Izaks et al., 2011; Kuiper et al., 2017; Ross, 2014). Figural fluency is sensitive to early changes in cognitive function. Defective performance of figural fluency tasks results from not only productivity limitations, that is, difficulties in initiating and sustaining the goal-directed activity, but also deficits in flexibility and strategic behavior (Ross, 2014; van Eersel et al., 2015).

Previous data suggest that the association between aging and changes in the memory processes is mediated by the executive system (Bisiacchi et al., 2008; Fisk & Sharp 2004), but the specific nature of this relationship is still not fully explained (Zink et al., 2021). The relations between executive functions and verbal memory measures are reported in several studies, but relatively less is known about the connections between executive functions and visual memory in the process of aging

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(Angel et al., 2010; Blankenship et al., 2016; Duff et al., 2005; Zawadzka & Domańska, 2018).

Within visual memory, age-related changes are observed especially in tasks with considerable cognitive requirements, but they may not be distinct in simple visual memory tests, when retrieval is automatic (Bennett et al., 2001; Borella et al., 2008; Jenkins et al., 2000; Ortega et al., 2012; Park et al., 2002). Cognitive activities, like visual memory retrieval during learning process, likely require high levels of executive control that are not equally available across the life span (Bisiacchi et al., 2008; Brown et al., 2012; Ortega et al., 2012). If the tasks are more demanding, that is, they engage executive control, older adults may change their typical manner of retrieval performance. In such conditions, the observed differences in visual task accomplishments may be the function of the range of executive involvement (Ortega et al., 2012).

Data presented by Bisiacchi et al. (2008) suggest that the cognitive decline between young-old and old-old individuals affects some of the executive functions that may be associated with visuo-spatial memory. Christian et al. (2015) showed that visual learning is influenced by some aspects of executive functions, that is, the ability to inhibit distractors and select task-relevant features. This is in line with Kuai and Kourtzi's (2013) approach that visual learning in aging might be limited by visual selection processes, probably due to weakening of inhibitory processes or attentional functions in aging. Christian et al. (2015) revealed that older participants have difficulties in inhibition of irrelevant details and it was assumed that older adults may attempt to compensate for this cognitive capacity by drawing on the use of learning strategies.

In the light of neurocognitive aging hypotheses, the performance of effortful visual learning tasks may be connected with engagement of compensatory strategies built on executive functions. These findings correspond with the posterior-anterior shift in aging (PASA; Davis et al., 2008) model which indicates an age-related reduction in brain activity in posterior parts of the brain and increased activity in anterior areas, especially within the prefrontal cortex (Kaufman et al., 2016). This assumption is also supported by the compensation-related utilization of neural circuits hypothesis (CRUNCH; Reuter-Lorenz & Cappell, 2008) integrating brain imaging data with cognitive behavioral effects that accompany aging. Task performance in older adults involves more neural circuits engagement than in younger individuals, especially including overactivation of frontal or bilateral recruitment what may reflect increasing contribution of executive functions to effectiveness of memory activities (Jamadar, 2020; Martins et al., 2015; Reuter-Lorenz & Park, 2010). The idea was developed in the scaffolding theory of cognitive aging-revised (STAC-r). It shows selective changes in the aging brain that reflect neural decline as well as compensatory neural recruitment, especially in the prefrontal cortex. The theory takes life-course factors that enhance or deplete neural resources into account (Reuter-Lorenz & Park, 2014). These concepts suggest that as age advances and cognitive abilities diminish, older adults rely more heavily on neural reserve (Martins et al., 2015) and undertake compensatory efforts on the basis of the prefrontal systems activity.

Activation of neural reserve in aging depends on various conditions and transfers to highly heterogeneous individual trajectories of cognitive aging (Giogkaraki et al., 2013; Oosterman et al., 2021; Reed et al., 2010). The differences can be explained in the framework of cognitive reserve which is assumed to reduce the risk of cognitive decline by fostering the use of compensatory cognitive processes. Cognitive reserve is often conceptualized as a capacity to cope better with the cognitive changes associated with aging by promoting more flexible usage of cognitive processes, for example, new strategies (Constantinidou et al., 2012; Frankenmolen et al., 2018; Satz et al., 2011). It is progressively built through cognitively demanding and stimulating experiences, such as education (Reed et al., 2010). Years of formal education is commonly used as the single proxy measure of the cognitive reserve concept. Widely provided rationale for using formal education as a proxy of cognitive reserve is based on the assumption that it generates new cognitive strategies to compensate for aging-related cognitive changes (Giogkaraki et al., 2013).

Previous studies have shown that higher levels of cognitive reserve allow to cope with brain dysfunction through some forms of active compensatory strategies better than in cases of lower reserve (Ferguson et al., 2021; Frankenmolen et al., 2018; Roldán-Tapia et al., 2017). That means that cognitive reserve is regarded as playing a moderating part in the associations between brain pathology and the expression of the pathology and should not be considered a factor protecting the brain against the development of brain pathology (Brickman et al., 2011; Giogkaraki et al., 2013; Singh-Manoux et al., 2011).

Considering all the above findings, it can be concluded that in normal aging, a decline is observed both on executive function and visuo-spatial learning tasks characterized by considerable cognitive requirements. A similar pattern was expected in individuals with hypertension assuming a continuum between normal and pathological aging. The prevalence of arterial hypertension, the most common cardiovascular disease, increases with age. Because of lack of fully satisfying control of this health condition, it may contribute to cognitive problems (Adămuțiu & Manițiu, 2012; Debette et al., 2011; Gottesman et al., 2014; Jaiswal et al., 2010). What is worth underlying, the impairments of cognitive abilities in this population are not global, which is indicated by inconsistent research results. A lower level of functioning in such cognitive areas as attention, memory, executive functions, and speed of cognitive processing was revealed by untreated participants with hypertension compared to the group with normal parameters in this range (Saxby et al., 2003). However, the differences were not found in the range of accuracy, cognitive flexibility, and motor speed (Kalra et al., 1993; Saxby et al., 2003). Hypertension is treated as one of the factors determining the pattern of cognitive functioning of patients (Waldstein & Katzel, 2001). Nevertheless, there are reports of a weaker effect of this factor on cognitive functioning among older patients over 65 (Kennelly & Collins, 2012). The relationship between chronic hypertension and cognitive decline is not linear and, in clinical practice, shows a high degree of complexity, particularly in older people (Bădilă et al., 2015; Canavan & O'Donnell, 2022; Jaiswal et al., 2010; Kelly et al., 2016; Thorvaldsson et al., 2012).

Therefore, the current study aimed to extend the previous research by examining: (a) the effect of age and educational attainment (treated as one of the proxy measures of cognitive reserve) on selected aspects of executive functions (i.e., processing speed, cognitive flexibility, productivity, and cognitive control) and visual learning in older adults with hypertension while controlling the time from diagnosis, and (b) the contribution of the selected aspects of executive functions to visual learning in adults with hypertension at different stages of aging. We assumed that the current study, together with future research, may help to better characterize the relatively early stages of the aging process in individuals with hypertension who are in the risk group of brain pathology.

METHOD

Participants

The study comprised 102 ambulatory treated adults with hypertension aged 51-80 (see Table 1). Power analysis was conducted with G* Power 3 (Faul et al., 2007) designed as a general stand-alone power analysis program for statistical tests. The predictive power of the data was assessed through a compromise power analysis. For analysis of covariance (ANCOVA) design, the total sample size (N = 102) provided sufficient power ($1 - \beta = 0.96$) to detect a medium effect size when alpha is set at 0.05. For the regression analysis, the sample size (51-60 group: n = 29; 61-70 group: n = 46; 71-80 group: n = 27) provided sufficient power ($1 - \beta = 0.79$; $1 - \beta = 0.86$; $1 - \beta = 0.78$, respectively) to detect a medium effect size when alpha is set at 0.05.

An extended interview was carried out with each participant. At the early selection stage, we excluded individuals with severe hearing and vision deficits which were not corrected by glasses and so forth. Patients treated for diabetes, endocrinological, neurological, and psychiatric problems were also excluded from further examination. To include adults with no dementive signs, participants who scored below 25 in the Mini-Mental State Examination (Folstein et al., 1975) were not involved into the study. The enrolled participants were divided into three subgroups based on age, that is, consecutive decades: 51-60, 61-70, and 71-80. The time from hypertension diagnosis was recorded and included into further considerations. As the groups differed with respect to the time from diagnosis, this variable was controlled within ANCOVA model. There were no statistically significant differences in education level between the groups (see Table 1). Subjects participated in the study voluntarily, after providing informed consent for the participation. All data included in this manuscript was obtained in compliance with regulations of our institutions, and research was completed in accordance with the guidelines of the Helsinki Declaration.

Measures

Two tests were applied to measure executive functions: Color Trails Test (CTT; Polish adaptation by Łojek & Stańczak, 2012) and Ruff Figural Fluency Test (RFFT; Polish adaptation by Łojek & Stańczak, 2005). The Polish version of Visual Learning and Memory Test for Neuropsychological Assessment (DCS; Weidlich & Lamberti, 1997) delivered indicators of visual learning. All of these measures base on nonverbal visual material.

Two parts of CTT (Łojek & Stańczak, 2012) were administered. In CTT1, participants connect circles numbered 1 through 25 in sequence. The completion time is regarded as the index of processing speed. In CTT2, participants connect numbered circles from 1 to 25 in sequence alternating between two colors: pink and yellow. The completion time of the second part and the interference index are indicators of cognitive flexibility treated as the ability to transition between at least two processes or tasks (i.e., alternating attention between two goals). The interference index (CTT-Int) counted according to manual (CTT2 time subtracted from CTT1 time and the outcome divided by CTT1; Łojek & Stańczak, 2012) attempts to remove the speed element from the test evaluation. Other additional indices of CTT performance, for example, prompts, number sequence errors, and color sequence errors, were recorded, but because of infrequency of their prevalence among our participants, they were not included in the further analyses.

The RFFT is based on pattern (figures) drawing by the examined person on the basis of a uniform graphical scheme. The tested participants have to generate possibly the highest number of such patterns in a limited time, and each of them must differ from the others. The task leaves a large scope of freedom in original designs creation. The number of unique designs (RFFT-UD) is treated mainly as an indicator of productivity, that is, the ability to initiate and sustain the goal-directed activity. It also shows cognitive flexibility and individuals' capacities to plan the nonverbal activity. The number of perseverations (RFFT-PE) and error ratio (RFFT-ER, the number of perseverations divided by the number of unique connections) were analyzed in the study. They are treated as the indicators of one of cognitive control aspects (Łojek & Stańczak, 2005).

Diagnosticum für Cerebralschädigung nach F. Hillers (DCS; in Polish version, Weidlich & Lamberti, 1997) measures learning capacity and visual material recalling. Because of high cognitive demands of the DCS, it may be regarded as an age-decline sensitive method. Subjects reproduce with five short sticks nine symmetrical geometrical drawings displayed in succession. Six trials are allowed, although the goal of reproducing all drawings in one trial can be reached earlier. The maximum score for the number of correctly recalled figures (DCS-1-6), treated as the indicator of visual learning, was 54. The loss of recalled figures (DCS-F), perseverations (DCS-P), and total errors (DCS-E) were also analyzed.

Data Analysis

Statistical analyses were performed with SPSS software (version 26.0). The two-way ANCOVA model with executive function and visual learning as dependent variables, age and educational attainment as main effects, and the time from hypertension diagnosis as a covariate was conducted. In order to determine the potential correlation between the executive functions and visual learning, the Pearson's correlation coefficient was estimated. Regression analysis was performed to search for predictors of visual learning. Statistical significance was set at .05 for all analyses.

TABLE 1.
Comparison of Demographic Data and Cognitive Task Performance in the Tested Groups of Older Adults

	51-60 group (*n* = 29)	61-70 group (*n* = 46)	71-80 group (*n* = 27)	*F*(*p*)
Education (*M*/SE)	13.41/2.8	12.82/3.1	12.13/3.3	1.161 (.320)
Women/men (%)	72/28	76/24	74/26	-
The time from hypertension diagnosis (*M*/SE)	8.36/5.37	13.14/7.48	14.10/9.07	4.285 (.017)[a,c]
Executive function[AM] (*M*/SE)				
CTT1	61.06/6.42	71.04/5.23	88.07/7.34	3.745 (.029)[a]
CTT2	111.41/11.90	142.01/9.69	170.37/13.61	5.172 (.008)[a]
CTT-Int	.85/0.11	1.10/.09	.88/.13	1.928 (.153)
RFFT-UD	77.66/4.21	70.56/3.43	53.37/4.81	7.302 (.001)[a,b]
RFFT-PE	9.84/1.82	8.60/1.48	5.99/2.08	.968 (.385)
RFFT-ER	.14/0.04	.12/.03	.16/.04	.368 (.694)
Visual learning[AM] (*M*/SE)				
DCS-1-6	36.85/2.26	37.77/1.84	28.28/2.58	4.871 (.011)[a,b]
DSC-F	2.40/.41	2.14/.33	2.94/.47	1.010 (.369)
DCS-P	.65/.37	1.02/.30	1.48/.43	1.020 (.366)
DCS-E	2.93/.84	3.01/.69	4.88/.97	1.477 (.236)

Note. [a] = 51-60 versus 71-80, [b] = 61-70 versus 71-80; [c] = 51-60 versus 61-70 (post hoc Bonferroni test); CTT-Int = interference index, RFFT-UD = unique designs, RFFT-PE = perseverations, RFFT-ER = error ratio, DCS-1-6 = total trials 1-6, DCS-F = forgetting index, DCS-P = perseverations, DCS-E = errors – total, [AM] = adjusted standardized means in the two-way ANCOVA model while controlling the time from diagnosis of hypertension.
$p < .05$;

RESULTS

Executive Functions and Visual Learning After Controlling the Time from Hypertension Diagnosis - Effects of Age and Education

The goal of running a two-way ANCOVA was to determine whether there was an interaction effect between the two independent variables, age and educational attainment, in terms of the dependent variables, executive functions and visual learning after controlling for the covariate, the time from hypertension diagnosis. There were no statistically significant interactive effects of age and educational attainment for all indices of the CTT, RFFT, and DCS whilst controlling for the time from hypertension diagnosis: $F(4, 68) = 1.497$, $p = .213$, $\eta^2 = .81$ for CTT1; $F(4, 68) = 1.875$, $p = .125$, $\eta^2 = .10$ for CTT2; $F(4, 68) = 0.683$, $p = .606$, $\eta^2 = .04$ for RFFT-UD; $F(4, 68) = .534$, $p = .711$, $\eta^2 = .03$ for RFFT-PE; $F(4, 68) = 1.234$, $p = .305$, $\eta^2 = .07$ for RFFT-ER; $F(4, 68) = .245$, $p = .911$, $\eta^2 = .01$ for DCS-1-6; $F(4,68) = 1.389$, $p = .247$, $\eta^2 = .08$ for DCS-F; $F(4, 68) = .695$, $p = .598$, $\eta^2 = .04$ for DCS-P, $F(4, 68) = .827$, $p = .513$, $\eta^2 = .05$ for DCS-E.

The ANCOVA confirmed four main effects of age on some CTT, RFFT, and DCS scores after controlling for the time from hypertension diagnosis as the covariate. The analysis of CTT1, CTT2, and RFFT-UD showed the main effects of age, respectively, $F(2, 68) = 3.745$, $p = .029$, $\eta^2 = .10$; $F(2, 68) = 5.172$, $p = .008$, $\eta^2 = .13$; $F(2, 68) = 7.302$, $p = .001$, $\eta^2 = .18$. The main effect of age was also obtained for DCS-1-6, $F(2, 68) = 4.871$, $p = .011$, $\eta^2 = .13$. Further analysis using the post-hoc Bonferroni test revealed significantly longer time of CTT1 and CTT2 performance in the 71-80 group comparing to the 51-60 group. The participants from the oldest group obtained significantly lower scores in RFFT-UD than both the 51-60 and 61-70 groups. The DCS-1-6 score appeared significantly lower in 71-80 group in comparison to the 51-60 and 61-70 groups (see Table 1).

There were also statistically significant main effects of educational attainment on the following indices: CTT1, $F(2, 68) = 9.327$, $p < .001$, $\eta^2 = .22$; CTT2, $F(2, 68) = 10.678$, $p < .001$, $\eta^2 = .24$; RFFT-UD, $F(2, 68) = 4.957$, $p = .010$, $\eta^2 = .13$; DCS-1-6, $F(2, 68) = 6.734$, $p = .002$, $\eta^2 = .17$, after controlling for the effect of the time from hypertension diagnosis. Post-hoc analysis using the Bonferroni test showed statistically significant differences between primary, secondary, and university levels of education (see Table 2). Participants with primary education obtained lower scores on RFFT-UD than older adults with secondary ($p < .040$) and with university education ($p < .016$). Post-hoc tests revealed statistically significant differences between primary and secondary ($p < .001$) and primary and university education ($p < .007$) on CTT1. Similar effects were obtained for the CTT2 ($p < .001$; $p < .008$, respectively). Participants with primary education showed significantly lower results in DCS-1-6 comparing to older adults with university education ($p < .002$).

Relationships Between Selected Aspects of Executive Functions and Visual Learning

Considering the relationships between selected aspects of executive functions and visual learning, the Pearson's correlation coefficient was estimated for 51-60, 61-70, and 71-80 groups separately (see Table 3). In further analyses, a linear regression was conducted to identify the

TABLE 2.

Adjusted Standardized Means and Standard Errors (M/SE) for Executive Functions and Visual Learning Indices – the Main Effects for Educational Attainment (Post Hoc Bonferroni Test)

	Groups	Primary	Secondary	University
CTT1[a,b]	51-60	65.85/12.44	57.10/10.25	60.23/10.09
	61-70	92.47/8.39	56.01/9.63	64.66/9.18
	71-80	126.66/11.54	62.56/12.83	75.00/13.67
	Overall	94.99/6.28	58.55/6.26	66.63/6.38
CTT2[a,b]	51-60	128.28/23.05	101.18/19.00	104.78/18.69
	61-70	170.85/15.55	114.77/17.86	140.41/17.02
	71-80	250.47/21.38	112.22/23.78	148.42/25.33
	Overall	183.20/11.64	109.39/11.60	131.21/11.83
RFFT-UD[a,b]	51-60	72.51/8.15	83.80/6.72	76.67/6.61
	61-70	59.39/5.50	74.82/6.31	77.47/6.02
	71-80	38.07/7.56	55.54/8.41	66.50/8.96
	Overall	56.66/4.11	71.39/4.10	73.55/4.18
DCS-1-6[b]	51-60	31.01/4.37	36.32/3.60	43.21/3.54
	61-70	32.50/2.95	39.72/3.38	41.10/3.23
	71-80	20.62/4.05	30.28/4.51	33.92/4.80
	Overall	28.05/2.20	35.44/2.20	39.41/2.42

Note. [a] = primary versus secondary, [b] = primary versus university, RFFT-UD = unique designs, DCS-1-6 = total trials 1-6.

$p < .05$

potential contribution of processing speed, flexibility, productivity, and cognitive control to visual learning.

In the 51-60 group, there were statistically significant correlations between CTT1 and two indices of DCS: DCS-1-6, and DCS-F. The longer time of CTT1 performance, the lower DCS-1-6 score and the higher forgetting index (DCS-F). In this group, CTT2 was also correlated negatively with DCS-1-6. There were no statistically significant correlations between CTT-Int, RFFT-UD, or RFFT-ER and DCS indices (see Table 3). A linear regression revealed the following statistically significant impacts: CTT1 on DCS-1-6 ($\beta = -.518$, $t = -3.143$, $p = .004$, $R^2 = .268$), CTT1 on DCS-F ($\beta = .402$, $t = 2.283$, $p = .030$, $R^2 = .162$), and CTT2 on DCS-1-6 ($\beta = -.577$, $t = -3.670$, $p = .001$, $R^2 = .333$). CTT1 explained about 27% and CTT2 about 33% of total variance in DCS-1-6 scores.

In the 61-70 group, both CTT1 and CTT2 were statistically significantly and positively correlated with DCS-F. The longer time of CTT1 and CTT2 performance, the higher DCS forgetting index. In this group, statistically significant correlations between RFFT-UD and two indices of DSC, DCS-1-6 and DCS-P, were also confirmed. The more unique designs in the RFFT, the higher the number of correctly recalled figures and the lower the number of perseverations in the DCS. There were no statistically significant correlations between CTT-Int, RFFT-ER, and DCS indices (see Table 3). In this group, regression analysis revealed statistically significant impacts of CTT1 and CTT2 on DCS-F ($\beta = .402$, $t = 2.912$, $p = .006$, $R^2 = .162$, $\beta = .344$, $t = 2.432$, $p = .019$, $R^2 = .118$, respectively). There were also statistically significant effects of RFFT-UD on DCS-1-6 and DCS-P ($\beta = .450$, $t = 3.344$, $p = .002$, $R^2 = .203$; $\beta = -.316$, $t = -2.209$, $p = .032$, $R^2 = .099$, respectively). The RFFT-UD explained about 20% of total variability in DCS-1-6.

In the 71-80 group CTT1 and CTT2 were correlated negatively with DCS-1-6; but RFFT-UD was correlated positively with DCS-1-6. The correlations between executive function indexes (CTT1, CTT2, and RFFT-UD) and the following indices of DCS, DCS-P, DCS-E, and DCS-F, were not statistically significant. There were also no statistically significant correlations between CTT-Int, RFFT-ER, and the all DCS indices (see Table 3). The regression analysis showed a statistically significant contribution of CTT1, CTT2, and RFFT-UD to DCS-1-6 ($\beta = -.513$, $t = -2.930$, $p = .007$, $R^2 = .263$; $\beta = -.628$, $t = -3.955$, $p < .001$, $R^2 = .394$; $\beta = .677$, $t = 4.501$, $p < .001$, $R^2 = .458$, respectively). The results revealed that about 46% of DCS-1-6 can be predicted by RFFT-UD, about 26% by CTT1, and 39% by CTT2.

DISCUSSION

The first aim of the current study was to examine the effect of age and educational attainment on selected aspects of executive functions (i.e., processing speed, cognitive flexibility, productivity, and cognitive control) and visual learning in older adults with hypertension while controlling for the time from diagnosis.

We found no interaction between age and education. However, as anticipated, the main effects of age and education were identified. We revealed that there were age-related differences in processing speed, cognitive flexibility, and productivity.

The oldest group with hypertension presented the weakest performance in these dimensions of executive functions. In the range of processing speed and cognitive flexibility, they performed significantly worse than the youngest age group. The productivity pertaining to figural material differentiated the oldest group from the others. It appears that the middle group (61-70 years old) sustained relatively good level of goal-directed activity, maintaining visual information, coordinating action sequences and, what is interesting, these participants represented productivity similar to the youngest group and substantially better than the oldest one. It is worth underlining that in the light of neurocognitive models of aging (Davis et al., 2008; Jamadar, 2020; Martins et al., 2015; Reuter-Lorenz & Cappell, 2008; Reuter-Lorenz & Park, 2010), well-preserved productivity and cognitive flexibility in the 61-70 group with hypertension may be the source of compensatory reserve, while other cognitive processes decrease. Our study showed similar level of cognitive control meant as perseverative behavior in all examined age groups. This is not congruent with most previous research reporting decrease in cognitive control among the oldest individuals (Borella et al., 2008; Ferguson et al., 2021; Foldi et al., 2003; Xia et al., 2022). The repetition avoidance is only one of the indicators of cognitive control and does not comprise the complexity of executive control. In our study, the lack of differences between age groups with hypertension in cognitive control measured by the number of perseverations may be also partly explained as a result of the introduced exclusion criteria, especially those referring to the signs of dementia and psychiatric disorders. In these disorders, the problems with cognitive control

TABLE 3.

Correlations Among Executive Functions (CTT, RFFT) and Visual Learning (DCS)

		CTT1	CTT2	CTT-Int	RFFT-UD	RFFT-ER
51-60 group	DCS-1-6	−.518/.004**	−.577/.001***	−.098/.616	.359/.055	−.180/.351
	DCS-F	.402/.030*	.283/.137	−.230/.230	.175/.365	.229/.231
	DCS-P	.119/.537	−.087/.653	−.349/.064	.163/.398	.123/.525
	DCS-E	.096/.619	.151/.433	.040/.836	−.174/.366	−.087/.652
61-70 group	DCS-1-6	−.289/.050*	−.200/.183	−.080/.600	.450/.002**	−.167/.266
	DCS-F	.402/.006**	.344/.019*	−.027/.858	−.164/.275	.038/.802
	DCS-P	.058/.703	.125/.406	.101/.511	−.316/.032*	.068/.654
	DCS-E	.050/.744	.049/.748	.227/.134	−.275/.064	.027/.860
71-80 group	DCS-1-6	−.513/.007**	−.628/.001***	−.260/.220	.677/.000***	−.368/.065
	DCS-F	.349/.080	.217/.286	−.207/.333	−.187/.360	−.165/.420
	DCS-P	.206/.312	.111/.589	.054/.803	−.282/.164	.095/.644
	DCS-E	−.015/.943	.012/.954	.165/.441	−.005/.980	.051/.806

Note. CTT-Int = interference index, RFFT-UD = unique designs, RFFT-ER = error ratio, DCS-1-6 = total trials 1-6, DCS-F = forgetting index, DCS-P = perseverations, DCS-E = errors – total.

$^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$

recognized on the basis of the perseverative errors are consistent with clinical experiences. Our study confirms a nonsteady decline in executive functions within the tested participants with hypertension within three decades of the second half of human life, which is congruent with the previous assumptions that this decline is not linear and shows a high degree of complexity (Canavan & O'Donnell, 2022; Iadecola et al., 2016; Kelly et al., 2016). Our results contribute to the discussion how different components of executive functions change across the life span, especially in the older population with hypertension (Ferguson et al., 2021; Iadecola et al., 2016).

In the current study, age-related differences were most pronounced for efficacy of visual learning. The oldest group of participants with hypertension showed the lowest visual learning capacities while performing demanding memory tasks. The subjects at the age of 61-70 (the middle group) appeared to be closer to the level of performance to the youngest participants, what may reflect effective employment of neurocognitive resources in this age group. The age of 71-80 seems to bring the most pronounced exacerbation of complex visual learning processes. It is possible that the individuals at this age reach the resource limitations leading to decline in performance as demands increase, what is congruent with the neurocognitive aging hypotheses (Jamadar, 2020; Martins et al., 2015; Reuter-Lorenz & Park, 2010, 2014).

Examining the effect of education as one of the proxy measures of cognitive reserve on visual learning and executive functions, we found the diversity. Participants with secondary or university levels of education attainment revealed significantly better capacities in processing speed, cognitive flexibility, and productivity than subjects with a lower level of education, regardless of age. With respect to visual learning, the capacities were significantly different only between persons with lowest and highest levels of education. Our findings are congruent with previous studies underlining the relationship between education and cognition (Giogkaraki et al., 2013; Oosterman et al., 2021; van Hooren et al., 2007). The higher level of education maintains mental stimulation throughout life that facilitates preservation of cognitive functions. The stimulating and demanding life experiences progressively built individuals' cognitive reserve. It may be reciprocally related to preferred lifestyle and everyday decisions influencing, for example, regular physical activity or exposure to harmful substances (Klimova et al., 2017). Individuals with higher reserve are more effective in coping with cognitive changes associated with aging and co-occurring disease processes. They promote more flexible and intentionally controlled usage of cognitive processes (Giogkaraki et al., 2013). Low level of education seems to be related to less brain reserve capacity, and therefore, cognitive symptoms are more likely after brain abnormalities (Bisiacchi et al., 2008; Martins et al., 2015). This refers to the persistent cardiovascular factors such as hypertension, which may impact some aspects of cognitive functioning especially the sensitive spheres, in the most demanding and complex tasks. Performing them, the persons with high cognitive reserve may compensate for their cognitive difficulties by means of using more intentional strategies, while less educated persons with weaker cognitive reserve appear to have a greater risk of suffering from cognitive decline (Ferguson et al., 2021; Giorgkaraki et al., 2013; Reed et al., 2010; Roldán-Tapia et al., 2017; Singh-Manoux et al., 2011). Thus, the cognitive reserve comprising educational attainment may modify the course of cognitive deterioration observed in individuals with hypertension who are in the risk group for brain pathology (Adămuțiu & Manițiu, 2012; Debette et al., 2011; Gottesman et al., 2014; Jaiswal et al., 2010).

The second aim of the current study was to investigate the contribution of the selected aspects of executive functions in the range of processing speed, cognitive flexibility, productivity, and cognitive control to visual learning in hypertensive adults at different stages of aging. The capacity of executive functioning seems to be important for efficacy of visual learning loaded with quantitative indices of performance. Our findings are an argument for the connection of selected aspects of executive functions and visual learning and support the suggestion of Ortega et al. (2012) that in controlled retrieval, there may be differences in visual task performance as the function of variations in executive abilities. The pattern of neuropsychological disorders, in the course of brain degeneration of vascular etiology, involves executive dysfunctions and disturbances in the speed of information processing (Brookes et al., 2013; Brown et al., 2012; Canavan & O'Donnell, 2022; Iadecola et al., 2016). Hence, processing speed was taken into account as a characteristic likely contributing to successful visual retrieval. In all tested age groups, the processing speed exerted a significant influence on visual learning task performance. It was possible to predict about 26% of its variance both in the youngest and in the oldest tested groups, and 16% in the persons with hypertension aged 61-70. This suggests that the slow cognitive processing impairs efficacy of visual learning. Participants with slower processing speed may find themselves able to recall only part of visual patterns. The influence is recognizable even in the tasks which do not have to be completed within established time limits. It stays in line with previous research highlighting the role of processing speed for the understanding of cognitive functioning in aging (Brookes et al., 2013; Brown et al., 2012).

In attempts to understand the role of other aspects of executive functions in visual learning, we acknowledge that in the youngest participants with hypertension, cognitive flexibility impacts visual learning, but productivity as an executive function component does not contribute to visual learning. Relatively well-preserved cognitive flexibility appears to support visual learning in success rate of retrieving. The lack of contribution of productivity to visual learning implies that not all aspects of executive functions are engaged equally while the complex visual learning task is being performed. We assume that the youngest participants encode and retrieve visual information with relative ease and they utilize executive function reserve remotely.

A different pattern of relationships between executive functions and visual learning was identified in individuals with hypertension aged 61-70. In contrast with the youngest participants, productivity, treated as the ability to initiate, sustain the goal-directed activity and to plan nonverbal activity (Ross, 2014; van Eersel et al., 2015), appears to influence visual learning in this group. It is worth highlighting that it is the only tested group in which a significant impact of processing speed, cognitive flexibility, and productivity on mistakes, that is, forgetting and perseverations during visual learning test performance, was observed. Greater processing speed, cognitive flexibility, and productivity were associated with a lower number of perseverations and forgetting. These results suggest that it is the seventh decade of life in which a relevant decline both in executive functions and visual learning is not observed but the shape of relationships between them is evolving. Keeping up a relatively good level of visual learning performance in this age group demands more mental effort and wider range of utilization of cognitive reserve based on executive functions. This is consistent with some assumptions put forward by several authors that a general shift from automatic to more controlled forms of processing takes place with advancing age (Bouazzaoui et al., 2014; Craik & Rose, 2012).

It is worth noticing that in our study, the strongest impact of cognitive flexibility and productivity on visual learning was revealed in the oldest group with hypertension. These aspects of executive functions explained about 40% or more variance of visual learning. It means that the oldest participants required these components of executive functions to a greater extent than younger individuals to perform visual learning tasks. These results pertaining visual learning are congruent with the approach that older adults are more reliant on executive functions to sustain memory performance than younger adults (Bouazzauoi et al., 2014; Craik & Rose, 2012). In our oldest group, this age-related pattern surfaced in spite of executive function impoverishing. Substantially worse performance of visual learning may be partially accounted for by the fact that the available executive resources appear insufficient to undertake so intensive compensatory cognitive effort. The oldest individuals with hypertension relatively often abandoned the visual learning task in comparison with the younger participants, which is also reported by clinicians.

The level of cognitive flexibility, initiating and maintaining goal-directed action as well as planning of the nonverbal activity, may be regarded as the crucial aspects of executive functions which have the predictive power in relation to the complex visual learning capacities. In a previous study, the role of executive functions as significant cognitive resources supporting verbal learning, short- and long-term memory in older adults treated for hypertension was confirmed (Zawadzka & Domańska, 2018). For that reason, on the one hand, our findings partially confirm Satz et al.'s (2011) consideration of executive functions as a candidate measure of cognitive reserve. On the other hand, in our study, executive functions appeared to be sensitive to the changes associated with aging, what is in agreement with previous data (Klimova et al., 2017; Moreira et al., 2018; van Hooren et al., 2007). Relatively preserved executive functions may support the performance of complex visual memory and learning tasks. However, the progressing impairment related to age and intensified by pathological processes, like those caused by hypertension, may reduce cognitive resources engaged in compensatory effort (Canavan & O'Donnell, 2022; Iadecola et al., 2016; Waldstein & Katzel, 2001). If the retrieval is more demanding and the task is more difficult, cognitive resources in oldest persons may be not sufficient to perform normal learning operations (Ortega et al., 2012). Cognitive activities such as visual memory retrieval during learning process probably require high levels of executive control that are not always available in the eighth decade of life, particularly in individuals with additional health problems.

Strengths and Limitations

The current study contributes to analysis of the role of some components of executive function in visual learning. Strengths of the current study include the elaborate assessment of both executive functions and memory with visual nonverbal materials. The administered visual learning task based on the abstract patterns as learning material was found to be sensitive to cognitive changes, which may help to deepen the characteristics of the stages of cognitive aging including the profile of age-related differences in visual learning. However, some limitation of our study should be noted. The abstract patterns are far from daily life experiences, therefore, we acknowledge that such tests may be less applicable to individual daily memory functioning. In future studies, to increase the ecological value of the assessment, we recommend including measures based on picture material related to daily life. It would be fruitful to extend the range of age to investigate how individuals with hypertension from the earlier decade (41-50) might perform on complex executive and vulnerable to aging visual learning tasks, since in the light of Ferreira et al.'s (2015) findings, cognitive decline before the age of 50 can be detected with sensitive cognitive measures. Previous findings consistently showed that a hypertension diagnosis in midlife was associated with worse cognitive performance in late life (Canavan & O'Donnell, 2022; Iadecola et al., 2016). In the current study, we controlled the time from hypertension diagnosis and the presence of other medical conditions, but we did not gain the data about the blood pressure, which could develop the characteristics of individuals with hypertension.

It is worth considering the usage of multiple measures of cognitive control. We administered only the repetition avoidance as an indicator of cognitive control, which seems to be not sufficient to comprise the complexity of this concept. Nevertheless, some aspects of cognitive control (i.e., ability to monitor, self-correct, and stop the planned action as needed) are involved in indicators defined as reflecting other components of executive functioning (Diamond, 2013), for example, the completion time of CTT2 or the number of unique designs in the RFFT. In further projects, more comprehensive assessment of executive functions including new technologies, for example, virtual reality, covering executive functioning in everyday life (particularly complex cognitive control) is recommended.

Conclusions

In sum, cognitive aging in individuals with hypertension is heterogeneous and represents a nonsteady pattern of deterioration of executive functions and visual learning over the age of fifty. The age-related changes in the range of processing speed and cognitive flexibility occur gradually, which may result partially from great variety of individual aging trajectories. Regarding productivity, we found a relatively good level of functioning until the seventh decade of life and the most pronounced exacerbation was noted over 70. Deep analysis of ongoing cognitive changes can be interpreted in the context of mechanisms of mental activity that seem to transform with age. More executive resources, including productivity, are involved in visual learning in the seventh decade, which probably contributes to relatively well-preserved visual learning performance. The age of 71-80 unveils an evident decline in complex visual learning processes in spite of the greatest impact of executive functions on visual learning. It probably means reaching by these individuals with hypertension the limit of cognitive resources comprising executive compensatory reserve highlighted in the CRUNCH hypothesis (Reuter-Lorenz & Cappell, 2008). Our study suggests the need of using complex visual learning tasks as a measure sensitive to age-related changes and including executive function training into assisting programs for adults with hypertension, even in the middle-age. It may buffer against negative effects of pathological aging and vascular cognitive impairments.

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DATA AVAILABILITY

Data and materials for the study reported here are available from the corresponding author on reasonable request. The study was not preregistered.

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