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Research Article

The effect of age on executive functions in adults is not sex specific

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Abstract

Objective: Numerous studies have shown a decrease in executive functions (EF) associated with aging. However, few investigations examined whether this decrease is similar between sexes throughout adulthood. The present study investigated if age-related decline in EF differs between men and women from early to late adulthood. **Methods:** A total of 302 participants (181 women) aged between 18 and 78 years old completed four computer-based cognitive tasks at home: an arrow-based Flanker task, a letter-based Visual search task, the Trail Making Test, and the Corsi task. These tasks measured inhibition, attention, cognitive flexibility, and working memory, respectively. To investigate the potential effects of age, sex, and their interaction on specific EF and a global EF score, we divided the sample population into five age groups (i.e., 18–30, 31–44, 45–54, 55–64, 65–78) and conducted analyses of covariance (MANCOVA and ANCOVA) with education and pointing device as control variables. **Results:** Sex did not significantly affect EF performance across age groups. However, in every task, participants from the three youngest groups (< 55 y/o) outperformed the ones from the two oldest. Results from the global score also suggest that an EF decrease is distinctly noticeable from 55 years old onward. **Conclusion:** Our results suggest that age-related decline in EF, including inhibition, attention, cognitive flexibility, and working memory, becomes apparent around the age of 55 and does not differ between sexes at any age. This study provides additional data regarding the effects of age and sex on EF across adulthood, filling a significant gap in the existing literature.

Keywords: cognitive aging; inhibition; attention; working memory; cognitive flexibility

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Introduction

From every step you take to every decision you make, your actions and thoughts are underlain and guided by your executive functions (EF). EF is an umbrella term encompassing a large range of high-level cognitive abilities such as inhibition, working memory, attention, and cognitive flexibility (Goldstein & Naglieri, 2014). They rely on complex cerebral networks, notably comprising the prefrontal cortex and its numerous connections with other regions such as posterior associative cortices (Collette et al., 2005). These cognitive processes are ubiquitous since they ensure a goal-oriented cognitive control of individuals' behaviors and emotions in the everchanging environment (Zelazo & Lee, 2010). EF can be influenced by multiple factors inherent to individuals or their environment, such as age, education, and context (Goldstein & Naglieri, 2014).

EF undergo developmental changes throughout the lifespan. They emerge and develop from childhood through adolescence, stabilize during adulthood, and decline from mid-adulthood onward (De Luca & Leventer, 2008; Ferguson et al., 2021). This trajectory is primarily influenced by the maturation of the prefrontal cortex, although each executive function does not follow the exact same developmental pattern. For instance, children's cognitive flexibility, enabling them to switch between tasks, emerges and matures rapidly between 4 and 8 years old, but is one of the latest to decline (Anderson et al., 2008; De Luca & Leventer, 2008). Working memory matures gradually, reaching its peak in the twenties, but is the first to decline (Ferguson et al., 2021). On the other hand, sustained attention and inhibitory skills mature and decline more progressively (Anderson et al., 2008; De Luca & Leventer, 2008).

The EF decline coincides with the so-called "age-related cognitive decline" which includes a decrease in various cognitive abilities during adulthood, such as processing speed, language, and visuospatial abilities (De Luca & Leventer, 2008; Harada et al., 2013). Age-related decline of cognitive functioning is associated with functional and structural changes in the brain network, especially in the frontal, temporal, and parietal lobes (Cabeza et al., 2016; Harada et al., 2013). Several magnetic resonance imaging and diffusion tensor imaging studies have reported a global loss of gray and white matter in the brain associated with age (Brickman et al., 2006; Charlton et al., 2008; Grieve et al., 2007; Head, 2004; Raz & Rodrigue, 2006). Moreover, functional neuroimaging studies showed increased activation of the frontal lobes in the aging brain (Goh et al., 2013; MacPherson et al., 2002), which may be a compensatory mechanism to offset cognitive decline (Park & Reuter-Lorenz, 2009; Reuter-Lorenz et al., 2016). The prefrontal

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cortex seems to be particularly vulnerable to the effect of aging and has been associated with a significant and gradual decrease in EF (Craik & Salthouse, 2007; De Luca & Leventer, 2008; Goh et al., 2013; Reuter-Lorenz et al., 2016).

While most EF share key brain regions and connections, each EF relies on its distinct brain network (see Rodríguez-Nieto et al. (2022) for a meta-analysis). For example, brain activations associated with inhibition were identified in right fronto-temporal regions, the left insular lobe, and bilateral inferior parietal regions. Conversely, left-lateralized activation in regions of the frontal and parietal cortex appears to be specific to cognitive flexibility. Working memory involves the activation of fronto-parietal areas along with the cerebellum, the latter structure not being recruited in other EF (Rodríguez-Nieto et al., 2022). The executive component of attention is mainly associated with the anterior cingulate gyrus and lateral prefrontal cortex (Posner & Rothbart, 2007). Given the reliance on different brain networks, some disparity in developmental trajectories across different components of EF is expected.

It has been reported that age-related changes in the brain vary between sexes. For instance, Coffey et al. (1998) found that compared to women aged between 66 and 96 years old, men the same age had more cerebrospinal fluid in the lateral fissure of their brain, which is a marker of age-related atrophy in the frontal and temporal lobes. These authors then inferred that some morphological features of the brain seem to be sensitive to both age and sex and their interaction. In their study, Taki et al. (2013) examined sex-based differences in the aging brain and found an age-by-sex interaction effect on gray matter in the bilateral hippocampus, suggesting that women's hippocampi lose more neurons over time compared to men. The hippocampus, along with the frontal lobe, plays a crucial role in the EF network, suggesting that sex may influence the age-related EF decline. Although the literature on sex differences in the aging brain remains inconsistent, the findings of recent studies show that men exhibit more structural changes related to age than women, which may contribute to a steeper cognitive decline in men (Lemaître et al., 2005; Yang et al., 2022).

Despite the extensive literature on cognitive decline and sex differences in cognition, surprisingly few studies investigated the interaction effects of age and sex on EF. Given the heterogeneity of methods, research designs, and findings among existing studies, a consensus has yet to be reached regarding the effect of sex on age-related cognitive decline. For instance, Levine et al.'s (2021) examined cognitive abilities including EF in adults from five well-characterized prospective cohort studies in the U.S. and showed that the global EF score in women declines faster with age than in men. Using the Stroop task to target cognitive flexibility, Nooyens et al. (2022) reported that men's performance exhibited a steeper decline with age compared to women, a conclusion that contrasts with Levine et al. (2021) study. These findings do not align with those of McCarrey et al. (2016) which show no age-by-sex interaction effect on cognitive flexibility, as measured with the Trail Making Test. Thus, there is currently no scientific consensus regarding the effect of sex on age-related cognitive decline; some studies show no sex difference (Ferreira et al., 2014; Finkel et al., 2006; McCarrey et al., 2016) while others report a steeper decline in women (Levine et al., 2021) or men (McCarrey et al., 2016; Nooyens et al., 2022). Another key factor that could account for the lack of consensus is the limited age range in the study samples, as most of the previous research focused on adults aged 60 years or older (Gaillard et al., 2021a). Conducting studies that investigate this question across the entire adult span could contribute to a better understanding of the effect of age and sex interaction on EF. Thus, the present study aimed to determine if age-related decrease in EF, more specifically inhibition, attention (selective and divided), cognitive flexibility, and working memory, varies between men and women from early to late adulthood. Based on the literature, we predicted that performance for all EF will decline with age, but no confirmatory hypotheses could be made regarding sex considering the limited and contradictory existing studies.

Methods

Participants

A total of 302 adults (181 women) from the province of Quebec, Canada, aged between 18 and 78 years old ($M = 46.2$; $SD = 15.8$) participated in the study (see Table 1). All participants reported French as their primary language and had no history of diagnosed neurological or psychiatric disorders. Participants were recruited through social media and provided electronic consent to participate in this study, which was approved by the Human Research Ethics Committee of Université du Québec à Montréal (UQAM). This research was conducted in line with the Helsinki Declaration.

Online questionnaires

For all participants, a Qualtrics online questionnaire was completed prior to the cognitive EF assessment to document key sociodemographic factors that can potentially influence cognitive functioning, such as age, sex, education, and ethnicity (Williams & Klug, 1996). The questionnaire also included the pointing device examinees used to complete the cognitive tasks (i.e., trackpad or computer mouse). To evaluate the usability of our online cognitive battery test, a homemade survey was created using the Qualtrics platform. It was sent by email to the first 90 participants to document their ease to complete the tasks and their satisfaction, including information about their computer familiarity (items presented in Supplementary material).

Cognitive function assessment

The assessment of EF included four tasks, each evaluating a different cognitive domain (see Table 2). Each task was programmed with PsychoPy3, a software for the creation of experiments in behavioral sciences (Peirce et al., 2019). All tasks were computer-controlled, meaning that instructions, practice trials, and feedback were provided directly on the participant's screen, without the intervention of any experimenter. Tasks were randomly ordered for each participant using computer-based randomization, and the entire sequence took approximately 35 minutes. To centralize data and enable home-based remote assessment on personal computers via a URL, the PsychoPy tasks were converted into JavaScript and linked to the Pavlovia server platform (https://pavlovia.org) to host the experiments securely (Peirce et al., 2019). Pavlovia also allowed the cognitive assessment to be independent of an internet connection by automatically and temporarily downloading the tasks onto each participant's computer.

To ensure consistent stimulus size independent of monitor resolution and screen size for all participants, a calibration task was completed by the participants before the beginning of the cognitive assessment. A picture of a credit card was first displayed on the screen and the participants were asked to adjust its size (i.e., by

Table 1. Sociodemographic characteristics of participants

	Women		Men		Full sample	
	n	%	*n*	%	*n*	%
Sample size	181	60.1	121	39.9	302	
Age group (Mean years ± *SD*)						
18–30 (24 ± 3)	49	71	20	29	69	22.8
31–44 (39 ± 4)	37	55.1	31	44.9	68	22.5
45–54 (49 ± 4)	25	45.5	30	54.5	55	18.2
55–64 (60 ± 3)	46	67.6	22	32.4	68	22.5
65–78 (69 ± 3)	24	57.1	18	42.9	42	13.9
Education (highest level)						
High school	19	59.4	13	40.6	32	10.5
Diploma of vocational studies	19	59.4	13	40.6	32	10.5
College	75	69.4	33	30.6	108	35.8
Bachelor	51	57.3	38	42.7	89	29.6
Graduate studies	17	41.5	24	58.5	41	13.6
Ethnicity						
Caucasian	176	60.5	115	39.5	291	96.4
Other *	5	45	6	55	11	3.6
Pointing device						
Trackpad	79	66.4	40	33.6	119	39.4
Computer mouse	102	55.7	81	44.3	183	60.6

*Afro-American, Asian, African, Hispanic.

Table 2. Cognitive tasks and measurements

Task	Scoring measure	Cognitive domain
Flanker	Difference in reaction time between incongruent and congruent trials	Inhibition
Visual search	Difference in reaction time between the 25 distractors trials and the 10 distractors trials	Selective and divided attention
Trail Making Test	Difference in duration between Part B and Part A	Cognitive flexibility
Corsi	Number of squares of the longest successful sequence	Working memory

increasing or decreasing the line length using the arrows of their computer keyboard) until it reached one of a standard credit card. The collected data was then automatically inputted into the task script for each participant, enabling the normalization of the stimuli size among the entire sample, regardless of monitor size or resolution. Before each task, additional instructions including respecting viewing distance (i.e., one meter away from the screen) and removing any distractions during the whole experiment were also displayed on the screen. Practice trials with computerized feedback preceded every task to ensure the understanding of participants.

Flanker

The Flanker task is a neuropsychological tool used to assess inhibition (Erikson & Erikson, 1974). Our version of this five-minute task involved 80 trials in which a set of five arrows appeared in the center of the screen. As shown in Figure 1, each trial included a central arrow (i.e., the target) flanked by two arrows on each side (i.e., the distractors). Participants were instructed to indicate the orientation of the central arrow by pressing as fast as possible the corresponding arrow key on their keyboard. Half of the trials were congruent, meaning that the target and distractors pointed in the same direction (< < < < < or > > > > >). The other half of the trials were incongruent, meaning that the target and distractors pointed in opposite directions (< < > < < or > > < > >). Incongruent trials were expected to take longer to complete due to the interference caused by the flankers pointing in the opposite direction of the target. Therefore, the difference in reaction time between incongruent and congruent trials was used as an indicator of inhibition and referred to as the Flanker effect (Erikson & Erikson, 1974; Kopp et al., 1996).

Visual search

The visual search task consisted of the presentation of blue and red "T" and "L" letters on the screen. Participants were asked to press "L" on their keyboard if they located a blue "L" (i.e., target) amidst the other distractors (i.e., red "L" and blue "T"), or to press "K" if they did not locate any target. The red and blue colors were purposefully selected, as blue is the color least affected by color blindness (Birch, 2012). This choice was made to ensure that most colorblind individuals would still be able to distinguish the stimuli in the Visual search task. There were 25 trials in each of the four conditions (10, 15, 20, or 25 distractors), for a total of 100 trials. In 60% of the trials, the target "L" was present. Locating a specific target among similar distractors requires selective and divided attention, a cognitive effort known to be proportional to the number of distractors (Davis & Palmer, 2004; Wolfe & Horowitz, 2017). For instance, trials with 25 distractors are expected to be more challenging and time-consuming than trials with 10 distractors (Davis & Palmer, 2004). The average reaction time in the 10 distractors trials was subtracted from the average reaction time of the most difficult condition (25 distractors) as a measure of the attentional distractor effect.

Trail Making Test

The Trail Making Test (TMT) is a well-known instrument for the assessment of cognitive flexibility (Goldstein & Naglieri, 2014). In part A, which is a single trial, participants were asked to connect circles identified by numbers ranging from 1 to 25, in an incremental order. In part B, which also includes one trial, the 25 circles were either identified by a number or a letter and participants were asked to connect them by alternating between numeric and alphabetical orders (e.g., 1, A, 2, B, 3, C, etc.). This switching results in a longer execution time compared to Part A, which is typically interpreted as the cognitive effort associated with cognitive flexibility. This effect is commonly quantified in clinical neuropsychology by subtracting the execution time of Part A from that of Part B (Kortte et al., 2002; Sánchez-Cubillo et al., 2009). In the original task, the evaluator provides feedback to the participant in case of an error, which the participant must correct immediately. In our computerized version of the task, the incorrectly chosen circle turned red, indicating to pick another circle. The participant had to correct their answer before moving forward.

Corsi

The Corsi task is a commonly used tool for assessing direct visuospatial memory span and visuospatial working memory. The task involved the presentation of nine gray squares displayed on the screen. In each trial, a minimum of three and up to nine of these squares turned red in a particular sequence. In the first fourteen trials, referred to as the forward part, participants were asked to replicate the sequence by clicking on them in the same order. In the 10 subsequent trials, which constitute the backward part,

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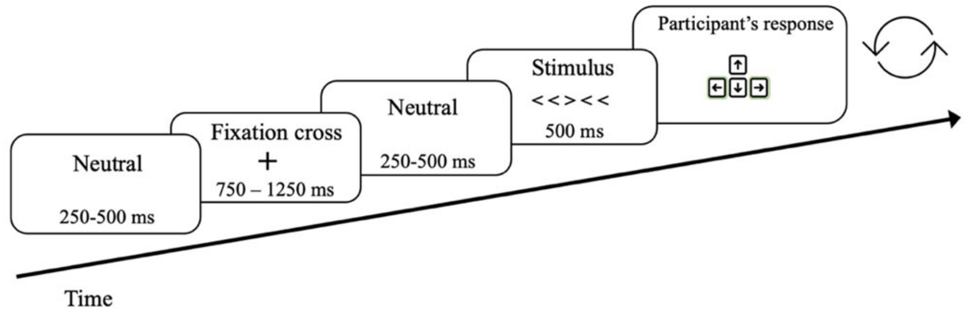

Figure 1. Trial sequence in the Flanker task.

participants were asked to reproduce the sequence backward (i.e., from the last square to the first). For both parts, after a correct answer, the sequence length increased by one square. After two incorrect responses, the sequence length decreased by one square. The number of squares from the longest successful sequence of the backward part was considered here as the measure for visuospatial working memory (Monaco et al., 2013).

Global score

Given that the reported sex disparities in cognition remain subtle, we added a global EF score combining our four EF measures to potentialize our ability to detect subdued effects. This global EF score was computed by averaging the Z scores of the individual tasks. To ensure that a higher global EF score equals higher performance, the Z scores of the Flanker, Trail Making Test, and Visual search variables were reversed given that originally, a higher score meant lower EF efficiency. Scores of participants who completed less than 3 out of the 4 tasks were left as missing values (i.e., 18% of the sample).

Statistical analysis

For each task, the most relevant metric according to the literature was derived (see Table 2). Thus, the condition measuring processing speed was subtracted from the condition assessing EF to obtain a specific metric for three out of the four tasks (Flanker, Visual search, and Trail Making Test). This approach minimizes potential interference from sensory-motor speed processing, which tends to decline with age (Deary & Der, 2005; Der & Deary, 2006). IBM SPSS Statistics (version 27.0.1) was used for descriptive statistics, data management, and all other statistical analyses. All tests were two-tailed, and the significance level was set at $p < 0.05$.

Univariate normality was assessed by inspecting outliers as well as skewness and kurtosis of the distributions. First, scores below −3.29 or over 3.29 on the standardized scale (Z score) were considered outliers and winsorized to ± 3.29 on the standardized scale, following the guidelines proposed by Tabachnick et al. (2019). For skewness and kurtosis, a threshold range of ±1 was used as a criterion of univariate normality. Flanker, Trail Making Test, and Visual search variables exceeded this threshold. After the square root transformations were applied, all variables respected the normality criterion.

Participants were divided into five age groups for the analyses (i.e., 18–30, 31–44, 45–54, 55–64, and 65–78). Given the importance of education on cognitive functioning (Bloomberg et al., 2021; Elias et al., 1997), this variable was included as a covariate in the analyses. Because almost all our participants were Caucasians, ethnicity was not included as a covariate in the models. To assess the effect of age and sex interaction on EF performance, a multivariate analysis of covariance (MANCOVA) was conducted using a factorial model with sex and age as independent variables, the scores of the four EF tasks as dependent variables and education as a control variable. To ensure that reaction times were not influenced by clicking or pointing device modality (trackpad vs computer mouse), which can be especially important for the Trail Making Test, this variable was also included in the models as a covariate. An additional analysis of covariance (ANCOVA) was executed employing the same factorial model (i.e., sex and age as independent variables and education and pointing device as control variables) but with the global EF score as the dependent variable.

Results

Usability survey data were successfully obtained from 53 participants (See Supplementary material). Results showed no age group or sex difference on any item, except for general technological proficiency and the occurrence of assessment-related technical issues. Although subjective rating (out of 100) was high in all participants, scores of participants 55 years or older ($M = 83.92$, $SD = 21.34$) were lower than those under 55 ($M = 92.98$, $SD = 10.21$) ($t\,(51) = 2.054$, $p = 0.043$). Regarding technical issues, a higher proportion of participants aged over 55 years reported experiencing more technical problems compared to those under 55 years old ($\chi^2 = 6.756$, $p = 0.009$).

Men's and women's performance on each task is summarized in Table 3 and illustrated in Figure 2.

The multivariate result (see Table 4) was not statistically significative for the interaction between age group and sex, meaning that differences in task scores between men and women remained consistent across all age groups, Pillai's Trace $(16{,}744) = 0.695$, $p = 0.800$. Taken separately, the results for the main effect of age were statistically significant, indicating that age had an impact on task performance scores, Pillai's Trace $(16{,}774) = 4.837$, $p < 0.001$. However, sex did not show a significant effect on EF performance scores, Pillai's Trace $(4{,}183) = 1.36$, $p = 0.25$.

Follow-up contrast analysis showed that in the Flanker task, participants from 18 to 54 years old had significantly smaller Flanker effect compared to the 55–64 years old ($p < 0.001$ and $p < 0.002$) (see Table 5 for details). However, participants aged between 65 and 78 years old had a significantly smaller Flanker effect compared to those in the 55–64 age group ($p = 0.03$). In the Visual search, participants belonging to the three youngest groups had a significantly smaller distractor effect compared to those in

Table 3. Descriptive statistics of cognitive performance

	Flanker (s) *Inhibition*		Visual search (s) *Attention*		Trail Making Test (s) *Cognitive flexibility*		Corsi (num. squares) *Working memory*		Global score	
Participants	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Men										
18–30	0.07	0.03	0.86	0.40	30.37	20.59	7.22	1.17	0.30	0.34
31–44	0.10	0.004	0.81	0.44	25.92	11.04	6.24	1.42	0.15	0.39
45–54	0.09	0.05	0.79	0.34	22.21	13.41	6.09	1.38	0.22	0.49
55–64	0.13	0.06	1.12	0.47	31.34	26.46	5.84	1.61	– 0.30	0.58
65–78	0.11	0.07	1.24	0.52	34.42	20.60	5.38	1.59	– 0.44	0.52
Women										
18–30	0.09	0.06	0.66	0.41	26.04	19.99	6.68	1.57	0.32	0.53
31–44	0.1	0.07	0.66	0.32	28.84	21.98	6.39	1.50	0.21	0.59
45–54	0.10	0.03	0.85	0.55	24.11	18.42	6.45	1.43	0.21	0.35
55–64	0.14	0.07	1.12	0.39	31.08	21.62	6.00	1.47	– 0.32	0.51
65–78	0.12	0.07	1.45	0.73	49.59	32.31	5.37	1.64	– 0.69	0.72

Lower scores at Flanker, TMT and VS correspond to a higher cognitive performance. Higher scores at Corsi and global score correspond to a higher cognitive performance. Attention measured by the Visual search task includes divided and selective attention. Abbreviations: *M*: mean, *SD*: standard deviation, (s): seconds, num.squares: number of squares.

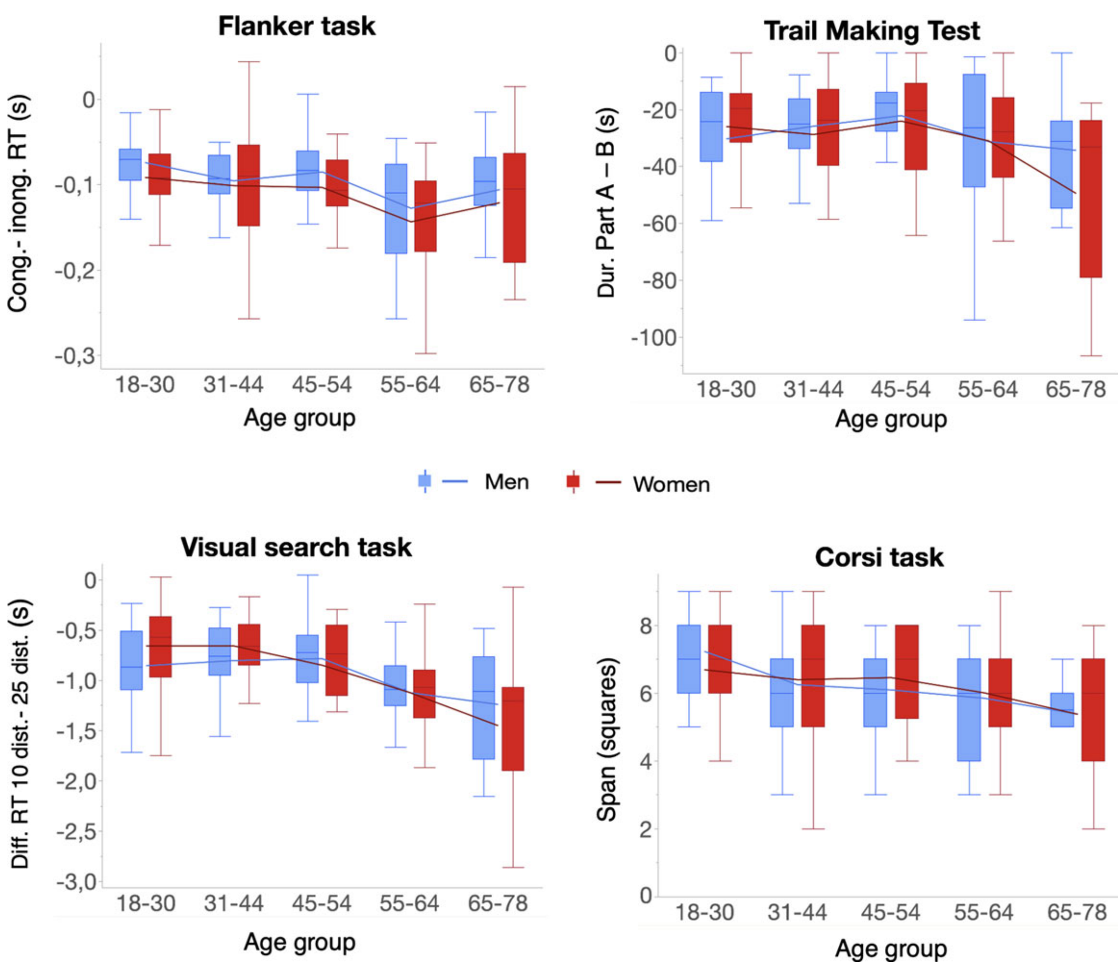

Figure 2. Performance scores of men and women of multiple age groups on cognitive tasks measuring inhibition (Flanker); cognitive flexibility (Trail Making Test); divided and selective attention (Visual search), and visuospatial working memory (Corsi). Y-axis details: Flanker: difference in reaction time between congruent and incongruent trials; TMT: difference in duration between Part A and Part B; VS: difference in mean reaction time between the trials with 10 distractors and those with 25 distractors; Corsi: number of squares of the longest sequence succeeded. Scores of the Flanker, Trail Making Test and Visual search were reversed for clarification purposes. Thus, a higher score corresponds to a higher EF efficiency. The bars represent the 95% confidence intervals.

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Table 4. Results from the MANCOVA univariate tests displaying the effect size of the variation of EF task scores explained by age, sex and their interaction

Independent variable	Dependant variable	*F (df)*	η_p^2	*p*
Age group				
	Flanker	4.32 (4, 186)	0.09	**0.002**
	Visual search	8.46 (4, 186)	0.15	**< 0.001**
	Trail Making Test	2.8 (4, 186)	0.06	**0.028**
	Corsi	3.9 (4, 186)	0.08	**0.005**
Sex				
	Flanker	2.37 (1, 186)	0.013	0.125
	Visual search	2.10 (1, 186)	0.011	0.149
	Trail Making Test	0.11 (1, 186)	0.0001	0.746
	Corsi	0.061 (1, 186)	0.0001	0.806
Age*Sex				
	Flanker	0.651 (4, 186)	0.014	0.627
	Visual search	0.059 (4, 186)	0.012	0.700
	Trail Making Test	1.49 (4, 186)	0.031	0.206
	Corsi	0.246 (4, 186)	0.006	0.912

Education and pointing device (i.e., trackpad or computer mouse) were included as covariates. Significant p-values are denoted in bold.

Table 5. P-value results of the follow-up analysis of the MANCOVA, reporting differences in scores between age groups

	Flanker	TMT	Visual Search	Corsi
18–30 vs 31–44	Ns	Ns	Ns	Ns
18–30 vs 45–54	Ns	Ns	Ns	Ns
18–30 vs 55–64	< 0.001	Ns	< 0.001	0.004
18–30 vs 65–78	Ns	0.012	< 0.001	< 0.001
31–44 vs 45–54	Ns	Ns	Ns	Ns
31–44 vs 55–64	0.002	Ns	< 0.001	Ns
31–44 vs 65–78	Ns	0.021	< 0.001	0.032
45–54 vs 55–64	0.002	Ns	0.006	Ns
45–54 vs 65–78	Ns	0.002	< 0.001	0.047
55–64 vs 65–78	0.033	Ns	Ns	Ns

Ns: non significant.

Table 6. Variation in reaction time between conditions in Visual search: Results from the mixed design ANCOVA displaying the effect size of the variation explained by age, sex and their interaction

Variable	*F (df)*	η_p^2	*p*
Trials*Age	10.69 (8.045)	0.149	**< 0.001**
Trials*Sex	0.765 (2.011)	0.003	0.466
Trials*Age*Sex	1.112 (8.045)	0.018	0.354

We applied a Greenhouse-Geisser correction to our data to account for the violation of the sphericity assumption. Education and pointing device were applied as covariates. Conditions in the Visual search vary in number of distractors displayed on the screen (10, 15, 20 or 25 distractors.) Abbreviations: df: degree of freedom; η_p^2: partial eta-squared. Significant *p*-value is denoted in bold.

both 55–64 and 65–78 age groups ($p < 0.01$). To confirm this effect across all four levels of distractors, we conducted an additional ANCOVA with the four conditions as the repeated measure, age, and sex as independent variables, and education and pointing device as control variables. This analysis indicated that reaction time varies across conditions [F (2.018,241) = 104.79, $p < 0.001$] (See Fig. 3 and Table 6). Simple contrast analysis revealed that reaction time significantly increases as the number of distractors increases ($p < 0.001$ between the four conditions). There was also a significant interaction between age and conditions [F (8.073,729) = 9.771, $p < 0.001$]. Regarding the Trail Making Test, participants under 55 years old had a significantly smaller cognitive flexibility effect compared to the participants from the 65–78 age group (18–30: $p = 0.01$; 31–44: $p = 0.02$; 45–54: $p = 0.002$). Finally, the follow-up analysis showed that the three youngest age groups had a significantly larger visuospatial working memory span compared to those in the 55–64 and/or the 65–78 age groups (18–30: $p < 0.001$; 31–44: $p = 0.03$; 45–54: $p = 0.03$). In summary, participants aged from 18 to 54 years old had better inhibition, attention, cognitive flexibility, and visuospatial working memory performances than those from the 55–64 and/or the 65–78 age groups.

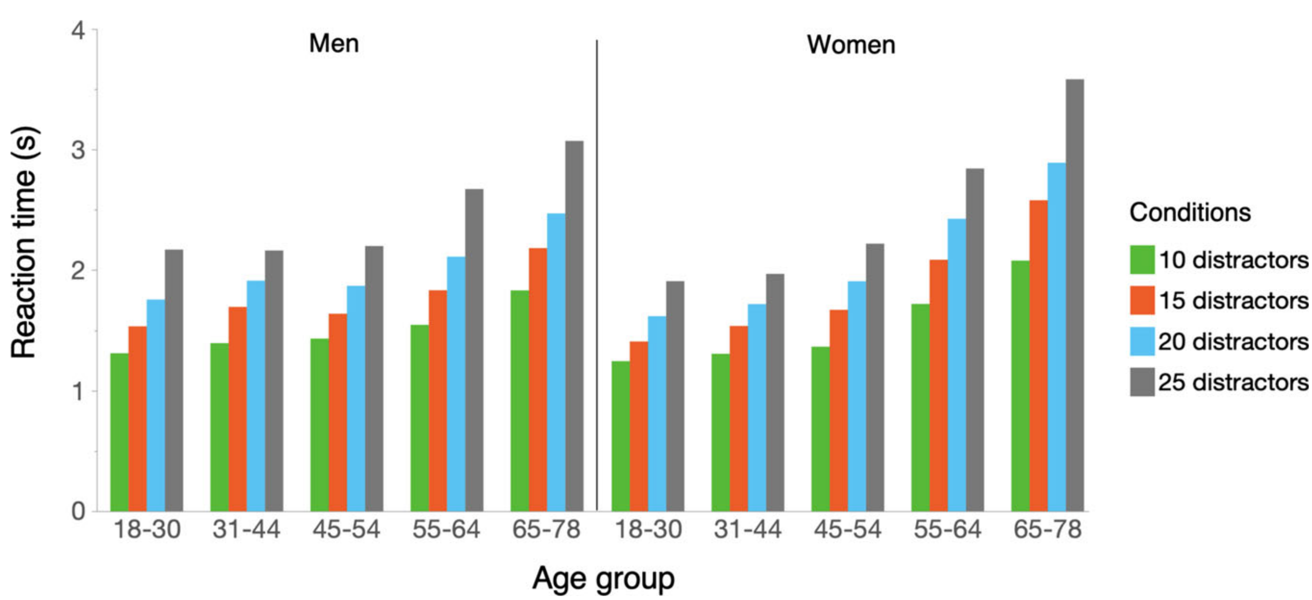

Figure 3. Reaction time of men and women during the four conditions of the Visual search, across age groups. Conditions vary in the number of distractors displayed on the screen (10, 15, 20 or 25 distractors).

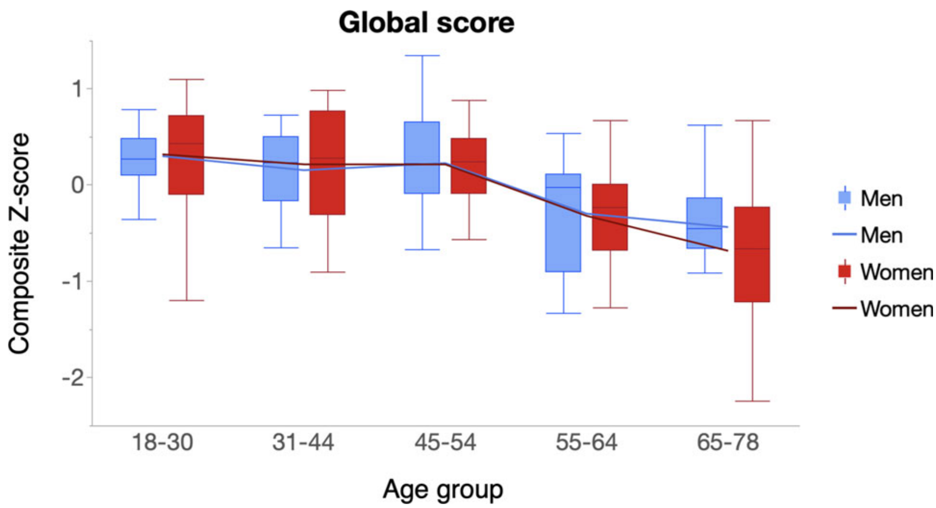

Figure 4. Global EF score of men and women of multiple age groups. The composite Z score corresponds to the average of the Z-scores from individual tasks. Thus, a higher score corresponds to higher cognitive performance. The bars represent the 95% confidence intervals.

Table 7. Results from the ANCOVA displaying the effect size of the variation of global EF score explained by age, sex and their interaction

F (df)	η_p^2	*p*
20.16 (4, 235)	0.255	< **0.001**
0.298 (1, 235)	0.001	0.586
0.464 (4, 235)	0.008	0.762

SD = standard deviation, df = degree of freedom, η_p^2 = partial eta-squared.
Education and pointing device are applied as covariates. Higher scores correspond to higher cognitive performance. Significant *p*-value is denoted in bold.

Regarding the effects of age and sex on global performance, the ANCOVA's results showed no statistically significant interaction effect of age and sex [$F\,(4{,}235) = 0.464$, $p = 0.762$], nor a significant main effect of sex [$F\,(1{,}235) = 0.298$, $p = 0.586$]. Once more, age is the only factor influencing global score [$F\,(4{,}235) = 20.16$, $p < 0.001$] (see Fig. 4 and Table 7). Thus, these results indicated that even though the global score varies with age, it remained similar between men and women of the same age group. The follow-up contrast analysis showed that the three younger age groups (i.e., 18–30, 31–44, and 45–54) had significantly higher global scores compared to the two older groups ($p < 0.001$). Moreover, participants aged between 55 and 64 years old also had a significantly higher global score compared to those aged between 65 and 78 ($p = 0.03$).

Considering that group categorization might reduce statistical power, we also conducted multiple regression analyses with age as a continuous variable to validate our findings. In our model, we included age and sex as independent variables, as well as education and pointing device as control variables. Consistent with our initial findings, no significant association with sex was found, while a significant association persisted between age and the Flanker task ($\beta = -0.244$; 95% Cl $= -0.001, 0.000$), $p < 0.001$), the Visual search task ($\beta = -0.387$; 95% Cl $= -0.016, -0.008$), $p < 0.001$), the Trail Making Test ($\beta = -0.191$; 95% Cl $= -0.434, -0.075$, $p < 0.01$), the Corsi task ($\beta = -0.323$; 95% Cl $= -0.043, -0.018$, $p < 0.001$), and the global score ($\beta = -0.486$; 95% Cl $= -0.023, -0.014$, $p < 0.001$). Of note, the relationship between age and task scores was more accurately explained by a quadratic model (see Figure 1 in Supplementary material).

Discussion

The aim of this cross-sectional study was to investigate whether age-related decline in executive functioning differed between sexes throughout adulthood. After controlling for education and the home-based assessment pointing device, we observed age-related differences on each EF measured (i.e., inhibition, attention, cognitive flexibility, working memory, and global EF score), but no evidence that these effects were influenced by sex. This is consistent with the review of Gaillard et al. (2021a) suggesting that the influence of sex on cognition is tenuous since most sex disparities reported in previous research are contradictory and/or have small effect sizes. Methodological features, like task sensitivity and difficulty, seem to influence the detection of those subdued sex disparities in cognition (Gaillard et al., 2021a; Zanto & Gazzaley, 2019). A larger sample size providing higher statistical power might help detecting such effects, as shown with studies using very large sample sizes (n > 1000) (Levine et al., 2021; McCarrey et al., 2016). Moreover, sex differences are more readily observable in studies comparing men's and women's brain functioning and networking (Gaillard et al., 2021b). For example, in a stop signal task involving inhibition, Li et al. (2006) found no performance differences between men and women but observed distinct neural network activations; men activated motor pathways more extensively, whereas women engaged neural circuits associated with visual associations and/or habit learning more extensively. Another investigation found that the fronto-parietal networks usually activated in the stop signal task were more activated in women than in men, along with their left amygdala (Gaillard et al., 2020). In addition, previous literature suggests that despite similar behavioral performances, women further rely on limbic and prefrontal structures to perform working memory tasks, whereas men showed more activation in parietal regions (Hill et al., 2014). Thus, different brain activations in men and women do not necessarily imply disparities in behavioral outcomes. It is possible that they rely on partly different cognitive strategies to execute a task while achieving comparable performances (Ramos-Loyo et al., 2022). In our study, both sexes might have employed different cognitive strategies during the assessment that were not reflected in our behavioral measures. Further investigations of sex disparities in EF would benefit from combining complementary behavioral measures and neuroimaging.

Despite the absence of sex effect on EF, we observed that, as expected, age had a major impact on each EF assessed here (inhibition, attention, cognitive flexibility, and visuospatial working memory). According to the global EF score, participants aged

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55 years and older underperformed in the EF assessment compared to younger adults (i.e., 18–54 years old). This is consistent with findings from cross-sectional and longitudinal studies showing that the onset of cognitive decline is mostly discernable around the 50s and 60s (Ferreira et al., 2015; Hedden & Gabrieli, 2004). Other findings suggested an even earlier onset of decline around 30 years old for some EF such as inhibition and working memory (Anderson et al., 2008; Ferguson et al., 2021). However, this hypothesis of the early onset of EF decline is far from consensual. In our study, results do not support this hypothesis since no age-related change was found in any EF measure among participants younger than 55 years old. Yet, these contradictory results might be partially attributable to methodological features such as the selected tasks and/or their sensitivity and level of difficulty.

In addition, we found that age-related changes slightly differed among individual EF (i.e., inhibition, attention, cognitive flexibility, and visuospatial working memory). For instance, age-related alterations in attention and inhibition efficiency were observed starting at 55 years old, while significant alterations in cognitive flexibility and working memory were mostly found starting at 65 years old. This agrees with prior findings suggesting that age-related changes might differ from one component of EF to another since they have been associated with different structure activation and region connections (Anderson et al., 2008; Zanto & Gazzaley, 2019). Yet, age-related disparities in EF efficiency such as inhibition, attention, cognitive flexibility, and visuospatial working memory, remain mainly detectable in mid to late adulthood (i.e., > 50 years old). Intriguingly, our results showed a higher inhibition efficiency in the 65–78 age group than in the 55–64 age group. This is inconsistent with various findings indicating that just like other EF, inhibition's decline emerges during adulthood and progresses with age (Borella et al., 2008; Ferreira et al., 2015; Mathis et al., 2009). This result is more likely attributable to the limited sample size of the oldest subgroup and/or random individual variation, rather than indicating an actual improvement of inhibition in the mid-60s.

Given the potential discomfort some older individuals may experience when using computers (Fox-Fuller et al., 2022), one could wonder whether this variable has influenced the age effect observed in our study. It is important to emphasize that most of the EF variables relied on a subtraction of the performance in two conditions to isolate a cognitive effect. Their value is thus based on intra-subject variability. Therefore, the computed measures are less dependent on potential inter-subject variability regarding familiarity with computer technology or motor difficulties. Moreover, among the 53 responders of the survey we sent to the initial 90 participants, 13 were 55 years or older and 92% of them reported using their computer daily. Those respondents also subjectively evaluated their computer proficiency rating at 8.3 out of 10 on average. Thus, it is unlikely that the age-related effects observed on EF are primarily attributed to technology discomfort.

Strengths and limitations

Our study is one of the few investigations examining the impact of age and sex interaction on EF across a broad age range. The inclusion of young adults when studying EF and aging is an important strength to provide a better understanding of the effect of age on EF, which is lacking in most existing studies. The utilization of a cross-sectional design was both advantageous and limiting to this study since it restricted the interpretation of the trajectory of cognitive decline but allowed greater information on the onset of age-related EF decline (Salthouse, 2010; Williams & Klug, 1996). Another limitation is that we used a single cognitive task to measure each EF. Incorporating additional tasks could potentially aid in identifying tasks suitable for detecting sex disparities in EF. However, the consistency observed in our results across cognitive tasks suggests a level of interdependence in EF, indicating that our findings are not solely dependent on the specific tasks employed in our study. Additionally, while our sample size is adequate, the predominantly Caucasian composition and the absence of adults aged over 78 years old limit the generalizability of our results. We also acknowledged that our home-based assessment might carry limitations such as slight variations in assessment conditions among participants. However, we took measures to mitigate these limitations (Marra et al., 2020). First, we used an initial screen calibration task to ensure a standardization of the stimuli sizes among our entire sample. Second, we examined the scores of the practice trials closely and excluded from the analyses participants who had over 50% error rate to ensure that our data primarily included participants who understood the task and did not have major visual deficiencies such as loss of acuity. We also ensured that cognitive tasks and data were independent of Internet connection quality by using the Pavlovia platform which automatically and temporarily downloads the task on the participant's computer, so the task's progress does not rely on an Internet connection. Moreover, we took precautions to limit the effect of other important factors such as cognitive depletion and sensory-motor speed by assessing the tasks in a random order and relying on strategic variables to target EF specifically. Remote assessment also provides experimental conditions closer to individuals' day-to-day life and may be less stressful for participants than in-laboratory assessment (Lupien et al., 2007).

In summary, the current work aimed to examine the age-related decline of EF, including inhibition, attention, cognitive flexibility, and working memory, in adults of both sexes. Our findings indicated that men and women performed similarly in cognitive tasks and that their EF efficiency underwent a comparable age-related decrease from young to late adulthood. While most research focussed on a specific age range when investigating sex disparities in EF, our study included a large span (i.e., 18–78 y/o) to examine the effect of age on EF from early to late adulthood. Although behavioral results were similar between men and women, we cannot exclude the possibility that both sexes use different strategies and/or brain networks when performing cognitive tasks. Further investigations involving different measures and techniques such as neuroimaging are needed to promote a more comprehensive understanding of EF development across age and sex.

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References

Anderson, V., Jacobs, R., Anderson, P. J., & Peter, J. (2008). *Executive functions and the frontal lobes : A lifespan perspective*. Taylor & Francis. WorldCat.org.

Birch, J. (2012). Worldwide prevalence of red-green color deficiency. *Journal of the Optical Society of America. A, Optics, Image Science, and Vision*, *29*(3), 313–320. https://doi.org/10.1364/JOSAA.29.000313

Bloomberg, M., Dugravot, A., Dumurgier, J., Kivimaki, M., Fayosse, A., Steptoe, A., Britton, A., Singh-Manoux, A., & Sabia, S. (2021). Sex differences and the role of education in cognitive ageing : Analysis of two UK-based prospective cohort studies. *The Lancet Public Health*, *6*(2), e106-e115–e115. https://doi.org/10.1016/S2468-2667(20)30258-9

Borella, E., Carretti, B., & De Beni, R. (2008). Working memory and inhibition across the adult life-span. *Acta Psychologica*, *128*(1), 33–44. https://doi.org/10.1016/j.actpsy.2007.09.008

Brickman, A. M., Zimmerman, M. E., Paul, R. H., Grieve, S. M., Tate, D. F., Cohen, R. A., Williams, L. M., Clark, C. R., & Gordon, E. (2006). Regional white matter and neuropsychological functioning across the adult lifespan. *Biological Psychiatry*, *60*(5), 444–453. https://doi.org/10.1016/j.biopsych.2006.01.011

Cabeza, R., Nyberg, L., & Park, D. C. (2016). *Cognitive neuroscience of aging : Linking cognitive and cerebral aging*. Oxford University Press.

Charlton, R. A., Landau, S., Schiavone, F., Barrick, T. R., Clark, C. A., Markus, H. S., & Morris, R. G. (2008). A structural equation modeling investigation of age-related variance in executive function and DTI measured white matter damage. *Neurobiology of Aging*, *29*(10), 1547–1555. https://doi.org/10.1016/j.neurobiolaging.2007.03.017

Coffey, C. E., Lucke, J. F., Saxton, J. A., Ratcliff, G., Unitas, L. J., Billig, B., & Bryan, R. N. (1998). Sex differences in brain aging : A quantitative magnetic resonance imaging study. *Archives of Neurology*, *55*(2), 169–179. https://doi.org/10.1001/archneur.55.2.169

Collette, F., Van der Linden, M., Laureys, S., Delfiore, G., Degueldre, C., Luxen, A., & Salmon, E. (2005). Exploring the unity and diversity of the neural substrates of executive functioning. *Human Brain Mapping*, *25*(4), 409–423. https://doi.org/10.1002/hbm.20118

Craik, F. I. M., & Salthouse, T. A.(Éds) (2007). *The handbook of aging and cognition* (3rd edn.). Psychology Press, https://doi.org/10.4324/9780203837665

Davis, E. T., & Palmer, J. (2004). Visual search and attention : An overview. *Spatial Vision*, *4*(5), 249–255. https://doi.org/10.1163/1568568041920168

De Luca, C. R., & Leventer, R. J. (2008). Developmental trajectories of executive functions across the lifespan. In *Executive functions and the frontal lobes : A lifespan perspective* (pp. 23–56). Taylor & Francis.

Deary, I. J., & Der, G. (2005). Reaction time, age, and cognitive ability : Longitudinal findings from age 16 to 63 Years in representative population samples. *Aging, Neuropsychology, and Cognition*, *12*(2), 187–215. https://doi.org/10.1080/13825580590969235

Der, G., & Deary, I. J. (2006). Age and sex differences in reaction time in adulthood : Results from the United Kingdom health and lifestyle survey. *Psychology and Aging*, *21*(1), 62–73. https://doi.org/10.1037/0882-7974.21.1.62

Elias, M. F., Elias, P. K., D'agostino, R. B., Silbershatz, H., & Wolf, P. A. (1997). Role of age, education, and gender on cognitive performance in the framingham heart study : Community-based norms. *Experimental Aging Research*, *23*(3), 201–235. https://doi.org/10.1080/03610739708254281

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception and Psychophysics*, *16*(1), 143–149. https://doi.org/10.3758/BF03203267

Ferguson, H. J., Brunsdon, V. E. A., & Bradford, E. E. F. (2021). The developmental trajectories of executive function from adolescence to old age. *Scientific Reports*, *11*(1), 1382. https://doi.org/10.1038/s41598-020-80866-1

Ferreira, D., Correia, R., Nieto, A., Machado, A., Molina, Y., & Barroso, J. (2015). Cognitive decline before the age of 50 can be detected with sensitive cognitive measures. *Psicothema*, *27*(3), 216–222. https://doi.org/10.7334/psicothema2014.192

Ferreira, L., Ferreira Santos-Galduróz, R., Ferri, C. P., & Fernandes Galduróz, J. C. (2014). Rate of cognitive decline in relation to sex after 60 years-of-age : A systematic review. *Geriatrics & Gerontology International*, *14*(1), 23–31. https://doi.org/10.1111/ggi.12093

Finkel, D., Reynolds, C. A., Berg, S., & Pedersen, N. L. (2006). Surprising lack of sex differences in normal cognitive aging in twins. *The International Journal of Aging and Human Development*, *62*(4), 335–357. https://doi.org/10.2190/C39X-9QHY-49DM-X9GJ

Fox-Fuller, J. T., Rizer, S., Andersen, S. L., & Sunderaraman, P. (2022). Survey findings about the experiences, challenges, and practical advice/Solutions regarding teleneuropsychological assessment in adults. *Archives of Clinical Neuropsychology*, *37*(2), 274–291. https://doi.org/10.1093/arclin/acab076

Gaillard, A., Fehring, D. J., & Rossell, S. L. (2021a). A systematic review and meta-analysis of behavioural sex differences in executive control. *The European Journal of Neuroscience*, *53*(2), 519–542. https://doi.org/10.1111/ejn.14946

Gaillard, A., Fehring, D. J., & Rossell, S. L. (2021b). Sex differences in executive control : A systematic review of functional neuroimaging studies. *European Journal of Neuroscience*, *53*(8), 2592–2611. https://doi.org/10.1111/ejn.15107

Gaillard, A., Rossell, S. L., Carruthers, S. P., Sumner, P. J., Michie, P. T., Woods, W., Neill, E., Phillipou, A., Toh, W. L., & Hughes, M. E. (2020). Greater activation of the response inhibition network in females compared to males during stop signal task performance. *Behavioural Brain Research*, *386*, 112586. https://doi.org/10.1016/j.bbr.2020.112586

Goh, J. O., Beason-Held, L. L., An, Y., Kraut, M. A., & Resnick, S. M. (2013). Frontal function and executive processing in older adults : Process and region specific age-related longitudinal functional changes. *NeuroImage*, *69*, 43–50. https://doi.org/10.1016/j.neuroimage.2012.12.026

Goldstein, S., & Naglieri, J. A. (2014). *Handbook of executive functioning (1re éd.).* Springer, https://doi.org/10.1007/978-1-4614-8106-5

Grieve, S. M., Williams, L. M., Paul, R. H., Clark, C. R., & Gordon, E. (2007). Cognitive aging, executive function, and fractional anisotropy : A diffusion tensor MR imaging study. *AJNR: American Journal of Neuroradiology*, *28*(2), 226–235.

Harada, C. N., Love, M. C. N., & Triebel, K. L. (2013). Normal cognitive aging. *Clinics in Geriatric Medicine*, *29*(4), 737–752. https://doi.org/10.1016/j.cger.2013.07.002

Head, D. (2004). Differential vulnerability of anterior white matter in nondemented aging with minimal acceleration in dementia of the Alzheimer type : Evidence from diffusion tensor imaging. *Cerebral Cortex*, *14*(4), 410–423. https://doi.org/10.1093/cercor/bhh003

Hedden, T., & Gabrieli, J. D. E. (2004). Insights into the ageing mind : A view from cognitive neuroscience. *Nature Reviews Neuroscience*, *5*(2), 87–96. https://doi.org/10.1038/nrn1323

Hill, A. C., Laird, A. R., & Robinson, J. L. (2014). Gender differences in working memory networks : A brainMap meta-analysis. *Biological Psychology*, *102*, 18–29. https://doi.org/10.1016/j.biopsycho.2014.06.008

Kopp, B., Rist, F., & Mattler, U. (1996). N200 in the flanker task as a neurobehavioral tool for investigating executive control. *Psychophysiology*, *33*(3), 282–294. https://doi.org/10.1111/j.1469-8986.1996.tb00425.x

Kortte, K. B., Horner, M. D., & Windham, W. K. (2002). The trail making test, part B : Cognitive flexibility or ability to maintain set? *Applied Neuropsychology*, *9*(2), 106–109. https://doi.org/10.1207/S15324826AN0902_5

Lemaître, H., Crivello, F., Grassiot, B., Alpérovitch, A., Tzourio, C., & Mazoyer, B. (2005). Age- and sex-related effects on the neuroanatomy of healthy elderly. *NeuroImage*, *26*(3), 900–911. https://doi.org/10.1016/j.neuroimage.2005.02.042

Levine, D. A., Gross, A. L., Briceño, E. M., Tilton, N., Giordani, B. J., Sussman, J. B., Hayward, R. A., Burke, J. F., Hingtgen, S., Elkind, M. S. V., Manly, J. J., Gottesman, R. F., Gaskin, D. J., Sidney, S., Sacco, R. L., Tom, S. E., Wright, C. B., Yaffe, K., & Galecki, A. T. (2021). Sex differences in cognitive decline among US adults. *JAMA Network Open*, *4*(2), e210169. https://doi.org/10.1001/jamanetworkopen.2021.0169

Li, C. R., Huang, C., Constable, R. T., & Sinha, R. (2006). Gender differences in the neural correlates of response inhibition during a stop signal task. *NeuroImage*, *32*(4), 1918–1929. https://doi.org/10.1016/j.neuroimage.2006.05.017

Lupien, S. J., Maheu, F., Tu, M., Fiocco, A., & Schramek, T. E. (2007). The effects of stress and stress hormones on human cognition : Implications for the field of brain and cognition. *Brain and Cognition*, *65*(3), 209–237. https://doi.org/10.1016/j.bandc.2007.02.007

MacPherson, S. E., Phillips, L. H., & Della Sala, S. (2002). Age, executive function and social decision making : A dorsolateral prefrontal theory of cognitive aging. *Psychology and Aging*, *17*(4), 598–609. https://doi.org/10.1037/0882-7974.17.4.598

Marra, D. E., Hamlet, K. M., Bauer, R. M., & Bowers, D. (2020). Validity of teleneuropsychology for older adults in response to COVID-19 : A systematic and critical review. *The Clinical Neuropsychologist*, *34*(7-8), 1411–1452. https://doi.org/10.1080/13854046.2020.1769192

Mathis, A., Schunck, T., Erb, G., Namer, I. J., & Luthringer, R. (2009). The effect of aging on the inhibitory function in middle-aged subjects : A functional MRI study coupled with a color-matched Stroop task. *International Journal of Geriatric Psychiatry*, *24*(10), 1062–1071. https://doi.org/10.1002/gps.2222

McCarrey, A. C., An, Y., Kitner-Triolo, M. H., Ferrucci, L., & Resnick, S. M. (2016). Sex differences in cognitive trajectories in clinically normal older adults. *Psychology and Aging*, *31*(2), 166–175. https://doi.org/10.1037/pag0000070

Monaco, M., Costa, A., Caltagirone, C., & Carlesimo, G. A. (2013). Forward and backward span for verbal and visuo-spatial data: Standardization and normative data from an Italian adult population. *Neurological Sciences*, *34*(5), 749–754. https://doi.org/10.1007/s10072-012-1130-x

Nooyens, A. C. J., Wijnhoven, H. A. H., Schaap, L. S., Sialino, L. D., Kok, A. A. L., Visser, M., Verschuren, W. M. M., Picavet, H. S. J., & Van Oostrom, S. H. (2022). Sex differences in cognitive functioning with aging in the Netherlands. *Gerontologia*, *68*(9), 999–1009. https://doi.org/10.1159/000520318

Park, D. C., & Reuter-Lorenz, P. (2009). The adaptive brain : Aging and neurocognitive scaffolding. *Annual Review of Psychology*, *60*(1), 173–196. https://doi.org/10.1146/annurev.psych.59.103006.093656

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. K. (2019). PsychoPy2 : Experiments in behavior made easy. *Behavior Research Methods*, *51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Posner, M. I., & Rothbart, M. K. (2007). Research on attention networks as a model for the integration of psychological science. *Annual Review of Psychology*, *58*(1), 1–23. https://doi.org/10.1146/annurev.psych.58.110405.085516

Ramos-Loyo, J., González-Garrido, A. A., Llamas-Alonso, L. A., & Sequeira, H. (2022). Sex differences in cognitive processing : An integrative review of electrophysiological findings. *Biological Psychology*, *172*, 108370. https://doi.org/10.1016/j.biopsycho.2022.108370

Raz, N., & Rodrigue, K. M. (2006). Differential aging of the brain : Patterns, cognitive correlates and modifiers. *Neuroscience & Biobehavioral Reviews*, *30*(6), 730–748. https://doi.org/10.1016/j.neubiorev.2006.07.001

Reuter-Lorenz, P. A., Festini, S. B., & Jantz, T. K. (2016). Executive functions and neurocognitive aging. In *Handbook of the psychology of aging* (pp. 245–262). Elsevier, https://doi.org/10.1016/B978-0-12-411469-2.00013-3

Rodríguez-Nieto, G., Seer, C., Sidlauskaite, J., Vleugels, L., Van Roy, A., Hardwick, R., & Swinnen, S. (2022). Inhibition, shifting and updating : Inter and intra-domain commonalities and differences from an executive functions activation likelihood estimation meta-analysis. *NeuroImage*, *264*, 119665. https://doi.org/10.1016/j.neuroimage.2022.119665

Salthouse, T. A. (2010). Selective review of cognitive aging. *Journal of the International Neuropsychological Society*, *16*(5), 754–760. https://doi.org/10.1017/S1355617710000706

Sánchez-Cubillo, I., Periáñez, J. A., Adrover-Roig, D., Rodríguez-Sánchez, J. M., Ríos-Lago, M., Tirapu, J., & Barceló, F. (2009). Construct validity of the trail making test : Role of task-switching, working memory, inhibition/interference control, and visuomotor abilities. *Journal of the International Neuropsychological Society*, *15*(3), 438–450. https://doi.org/10.1017/S1355617709090626

Tabachnick, B. G., Fidell, L. S., & Ullman, J. B. (2019). *Using multivariate statistics* (7th edn.). Pearson.

Taki, Y., Thyreau, B., Kinomura, S., Sato, K., Goto, R., Wu, K., Kawashima, R., & Fukuda, H. (2013). A longitudinal study of age- and gender-related annual rate of volume changes in regional gray matter in healthy adults. *Human Brain Mapping*, *34*(9), 2292–2301. https://doi.org/10.1002/hbm.22067

Williams, J. D., & Klug, M. G. (1996). Aging and cognition : Methodological differences in outcome. *Experimental Aging Research*, *22*(3), 219–244. https://doi.org/10.1080/03610739608254009

Wolfe, J. M., & Horowitz, T. S. (2017). Five factors that guide attention in visual search. *Nature human behaviour*, *1*(3), 0058. https://doi.org/10.1038/s41562-017-0058

Yang, J., Qu, J., & Ma, H. (2022). Recent developments in understanding brain aging : Sex differences, mechanisms, and implications in diseases. *Ageing and Neurodegenerative Diseases*, *2*(3), 31–48. https://doi.org/10.20517/and.2022.03

Zanto, T. P., & Gazzaley, A. (2019). Aging of the frontal lobe. *Handbook of Clinical Neurology*, *163*, 369–389. https://doi.org/10.1016/B978-0-12-804281-6.00020-3

Zelazo, P. D., & Lee, W. S. C. (2010). Brain development. In *The Handbook of Life-Span Development*. John Wiley & Sons, Ltd, https://doi.org/10.1002/9780470880166.hlsd001004