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Do attentional capacities and processing speed mediate the effect of age on executive functioning?

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DISCLOSURE STATEMENT

The authors have no financial interest or benefit arising from the direct applications of the research.

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ABSTRACT

Introduction. The executive processes are well known to decline with age, and similar data also exists for attentional capacities and processing speed. Therefore, we investigated whether these two last *non-executive* variables would mediate the effect of age on executive functions (inhibition, shifting, updating, & dual-task coordination). **Method.** We administered a large battery of executive, attentional and processing speed tasks to 104 young and 71 older people and we performed mediation analyses with variables showing a significant age effect. **Results.** All executive and processing speed measures showed age-related effects while only the visual scanning task performance (selective attention) was explained by age when controlled for gender and educational level. Regarding mediation analyses, visual scanning partially mediated the age effect on updating while processing speed partially mediated the age effect on shifting, updating and dual-task coordination. In a more exploratory way, inhibition was also found to partially mediate the effect of age on the three other executive functions. **Discussion.** Attention did not greatly influence executive functioning in aging while, in agreement with the literature, processing speed seems to be a major mediator of the age effect on these processes. Interestingly, the global pattern of results seems also to indicate an influence of inhibition but further studies are needed to confirm the role of that variable as a mediator and its relative importance by comparison with processing speed.

KEYWORDS: executive functions, attention, speed of processing, mediation analyses

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INTRODUCTION

Executive processes were first described in the context of the central executive system of working memory (Baddeley, 1986) and the Supervisory Attentional System (SAS, Norman & Shallice, 1986) and were related to the integrity of frontal lobes. Thereafter, several authors (Damasio, 1995; Miyake et al., 2000; Stuss & Benson, 1986) have contributed to the fractioning of these processes. In their neuroanatomical model based on frontal lesion studies, Stuss & Levine (2002) describe four types of frontal abilities that are specific and interconnected: 1) the executive functions (EF) comprise processes such as inhibition, planning, mental shifting, decision taking, etc.; 2) auto-regulation and decision taking capacities (for the influence of emotion on these processes, see Damasio, 1995, 2010) ; 3) energization is dedicated to energy mobilization and allocation in order to quickly initiate goal-directed responses (Stuss, 2006); 4) metacognitive functions allow the representation of one's own mental states (auto-noetic consciousness) or that of other people (Theory of Mind) (Stuss, 2008; Stuss, 2011; Stuss & Levine, 2002). Finally, in their hierarchical model of consciousness levels, Stuss and Anderson (2004) propose that executive functions process information coming from sensorial systems and monitor goal-directed responses as a function of the stimulus.

Of particular relevance for our present study, the executive functions can be defined as a set of high level abilities required to deal with new, dangerous or complex situations. These functions are well needed to the production of behaviours that are goal-directed. The existence of the four distinct executive functions of inhibition, shifting, updating and dual-task coordination is now well acknowledged, based on single-case analyses of brain-damaged patients and individual difference studies in various target populations (e.g., Burgess & Shallice, 1996a, 1996b; Duncan, Johnson, Swales & Freer, 1997; Lehto, 1996; Robbins et al., 1998). However, a commonality of processes in executive functioning was also evidenced by Miyake et al. (2000). Using confirmatory factor analyses, these authors have demonstrated that, although dissociable, inhibition, shifting and updating functions remain inter-correlated. Miyake and colleagues proposed these inter-correlations could correspond to processes related to the maintenance of task goals and contextual information in working memory and/or some "basic" inhibitory processes necessary for executive functions to operate properly.

However, this commonality of processes could also be related to the intervention of attentional functioning and processing speed. As these mechanisms are constantly solicited, whatever cognitive activity we are engaged in (for a review, see Rabinovich, Tristan, & Varona, 2015), it could be expected that these variables play a certain role on executive functioning. In agreement with that proposal, Collette et al. (2005) showed that the functions of shifting, updating and inhibition recruited common parietal areas previously associated with attentional processes, more particularly attentional reorienting (Corbetta & Shulman, 2002; Dove, Pollmann, Schubert, Wiggins, & von Cramon, 2000; Gurd et al., 2002) and selective attention (Behrmann, Geng, & Shomstein, 2004; Coull & Frith, 1998; Wojciulik & Kanwisher, 1999). Moreover, a recent confirmatory factor analysis in young participants showed that these three executive functions, and also dual-task coordination, are directly influenced by processing speed and sustained attention, these two processes being underlay by alertness capacity (Hogge, Pérée, & Collette, submitted; see also Hogge, 2008).

Like executive functioning, attention is far from a unitary cognitive function (Posner & Boies, 1971). However, the actual characterization of its different components as well as their interrelations have not yet been well established. Corbetta and Shulman (2002) postulated the existence of two cerebral networks responsible for different attentional

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functions. The first one is known as the dorsal attention network (comprising the dorsal parietal and frontal cortices) and is involved in the cognitive goal-directed selection of sensory information and responses (top-down attention). The second one is known as the ventral attention network, is centered on the right temporoparietal junction and is dedicated to the detection of behaviorally relevant stimuli (stimulus-driven attention). Corbetta, Patel, and Shulman (2008) further postulated that both dorsal and ventral attention networks are also activated during reorienting processes. Based on the definitions of Posner and Petersen (1990), attentional functioning is currently frequently investigated by the Attentional Network Test (ANT; Fan, McCandliss, Sommer, Raz, & Posner, 2002) that simultaneously assesses the efficiency of the alerting, orienting, and executive attention brain networks[1] (Mahoney, Verghese, Goldin, Lipton, & Holtzer, 2011; Lu, Fung, Chan, & Lam, 2016; Zhou, Fan, Lee, Wang, & Wang, 2011).

One of the most influential attentional model in clinical practice was proposed by van Zomeren and Brouwer (1994) which distinguishes between "intensity" and "selectivity" of attentional processes. The *intensity* axe opposes alertness and sustained attention. Alertness refers to the ability to quickly react to a recurrent stimulus which is presented at irregular intervals, the stimulus being or not preceded by an alerting cue (tonic *VS.* phasic alertness). Sustained attention characterizes one's abilities to maintain an attentional investment during relatively long periods in order to react to frequent stimulations. The *selectivity* axe opposes selective attention and divided attention. The former function refers to a set of mechanisms allowing the focalization of attentional resources on a specific and limited part of information, in order to maximize processing efficiency. By contrast, the latter one is relatively similar to the concept of dual-task coordination and refers to the simultaneous processing of many sources of information but also to the conjoint realization of many tasks. The van Zomeren and Brouwer's model was selected to assess attentional functioning in the present study. As we conceptually distinguish between attention and executive concepts and as we were intended to fully assess the different components of attention, we preferred to use an attentional model that did not emphasize executive aspects of attentional functioning.

Finally, processing speed refers to the way people can implement fast response times (or reaction times) because of time-pressure or to avoid a decrease of performance (as in working memory tasks). While the simple time reaction tasks measure alertness, choice reaction time tasks are often used to assess the rapidity with which an individual carries out an elementary cognitive operation on the proposed stimuli. Consequently, choice reaction time tasks are classically used to measure processing speed (Chiaravalloti, Christodoulou, Demaree, & DeLuca, 2003).

It is now well-established that normal aging is associated with cognitive decline (Craik & Salthouse, 2000), particularly in tasks involving executive functions (De Beni & Borella, 2015; Podell et al., 2012; Salthouse, Atkinson, & Berish, 2003; West, 2000). In a cerebral point of view, prefrontal activity during cognitive tasks tend to be less lateralized in aged people, in comparison to young people. This reduction in hemispheric asymmetry could be attributed to two different processes: while some authors tend to assume a compensatory function (Cabeza, 2002), others claim the existence of a dedifferentiation process (Li & Lindenberger, 1999). The hypothesis of dedifferentiation raises the question of the separability of executive processes in aging. Some studies tend to show a dedifferentiation process in executive functions (de Frias, Dixon, & Strauss, 2006; Delaloye et al., 2009, Hedden & Yoon, 2006). For example, de Frias et al. (2006) were intended to test the factorial structure of four executive functioning indices (Hayling, Stroop, Brixton, and Color Trails). Their confirmatory factor analyses evidenced that a single-factor model gave the best fit to the data. However, individual differences among the four tasks were not fully attributed to the executive function factor. Therefore, the authors suggested that independent features may further explain the commonality between the executive tasks. In 2009, Delaloye et al. also failed to replicate the three-factor model of Miyake et al. (2000) in older people. In a very interesting study, de Frias, Dixon, and Strauss (2009) examined the structure of the executive functions (inhibition, shifting, and updating) between three groups of older individuals characterized by different cognitive status: cognitively elite (CE), cognitively normal (CN), and cognitively impaired (CI). Their analyses confirmed a three-factor model for the CE group and a one-factor fit for the two other groups. The authors concluded that CE older adults are maybe aging in a more successful manner, leading them to exhibit an executive functioning structure resembling that of young people. By contrast to these studies, Vaughan & Giovanello (2010) demonstrated, thanks to structural equation modeling, that the three main executive functions postulated in Miyake et al. (2000) are also better represented by a three-factor model in older people.

Moreover, although the executive functioning decreases in efficiency with age, the different functions do not undergo a general decline. Rather, many studies evidence that if some aspects become impaired with aging, other remain well preserved (Borella, Delaloye, Lecerf, Renaud, & de Ribaupierre, 2009; Collette et Salmon, 2014; Cona, Arcara, Amodio, Schiff, & Bisiacchi, 2013; Ludwig, Fagot, & de Ribaupierre, 2011; Salthouse et al., 2003; Taconnat & Lemaire, 2014 ; Vallesi, Hasher,& Stuss, 2010). For example, with regard to shifting abilities, older people would meet difficulties to maintain and to manipulate two mental plans in working memory but not to alternate between these plans (Kray, Eber, & Lindenberger, 2004; Verhaeghen & Cerella, 2002). Regarding updating, aged people would meet difficulties in the process that consist in suppressing irrelevant (i.e., no more relevant) information in working memory but have preserved storage abilities (De Beni & Palladino, 2004). In the inhibitory domain, voluntary/intentional abilities seem well to decrease with age while automatic inhibition would be preserved (Collette, Germain, Hogge & Van der Linden, 2009; Hogge, Salmon, & Collette, 2008). In this sense, Borella, Ludwig, Dirk, and de Ribaupierre (2011) showed a lack of correlation between their two inhibition measures (interference index and negative priming index), leading them to the assumption that inhibition is a multidimensional construct (Borella, Carretti, & De Beni, 2008; Borella et al., 2009; de Ribaupierre, 2001; de Ribaupierre, Borella, & Delaloye, 2003; Ludwig et al., 2010). Another example comes from Shilling, Chetwynd, and Rabbitt (2002) who administered aged people with four inhibitory task considered as being variants of the Stroop task and found low correlations between these different measures. This finding suggests, in the one hand, that inhibition is not a unitary process and, on the other hand, that aging does not impair inhibition in all of its different aspects.

All these cognitive impairments are usually seen according two different theoretical approaches. The *analytical approach* claims that cognitive aging would directly impair the cognitive components for which decreased performances are observed. For example, a greater interference effect in a Stroop task will be interpreted as a deficit in the inhibitory function in older people. By contrast, the *global approach* suggests that the cognitive differences linked to age might be explained by a number of general cognitive factors ranging from diminished working memory resources (Craik, Morris, & Gick, 1990) and decreased processing speed (Salthouse, 2000) to sensorial function integrity (Li & Lindenberger, 2002). Today, cognitive decline seems to be viewed as being explained by some general factors as well as impairment in some specific cognitive components. Therefore, it would be very interesting to test whether certain non-executive factor such as processing or attention would explain some decrements in executive functions in normal aging.

Indeed, with advancing age, some changes are also reported in non-executive processes that could influence executive functioning efficiency. Furthermore, there is a general agreement that processing speed decreases with age (Albinet, Boucart, Bouquet, & Auddifren, 2012; Cona et al., 2013; Manard, Carabin, Jaspar, & Collette, 2014; Salthouse, 1992; Salthouse, 1993; Salthouse, 1994a, Salthouse, 1994b; Salthouse, 1996; Salthouse & Babcock, 1991; Salthouse & Meinz, 1995; Salthouse, 2000; Salthouse et al., 2000).

As very well summed up in Lecerf, de Ribaupierre, Fagot, & Dirk (2007), cognitive performances in older people are mediated by processing speed (de Ribaupierre, 1995; Salthouse, 1992), working memory (Baddeley & Hitch, 1974; Baddeley, 1986) and inhibition (Hasher & Zacks, 1988). Some authors further assume that these three mechanisms are simultaneously playing a role (de Ribaupierre, 2000). It seems that processing speed is the most influent mediator between age and fluid cognition (de Ribaupierre & Lecerf, 2006; Saltouse & Meinz, 1995). In that context, processing speed seems to be particularly relevant to explain the age-related inhibitory decline (de Ribaupierre, 1995; Hogge et al., 2008; Salthouse, 1992; Salthouse & Meinz, 1995; Verhaegen & Cerella, 2002; Verhaeghen & De Meersman, 1998). Likewise, Fisk & Sharp (2004) found an age effect on shifting but neither on inhibition nor updating when processing speed is controlled. By contrast, other authors did find this influence of processing speed for the function of shifting (Kray & Lindenberger, 2000; Salthouse et al., 2000) as well as updating (Sylvain-Roy, Lungu, & Belleville, 2015). Finally, some studies have shown that difficulties in dual-task coordination are not necessarily met when processing speed is controlled (Baddeley, 2001).

If the influence of processing speed on cognition seems well established, no study has ever tried to assess the effect of attentional variables on executive efficiency in normal aging although some studies have shown performance decrements in some attentional measurements. When related to the model proposed by van Zomeren and Brouwer (1994), these studies tend to suggest the presence of an age effect more often on the *selectivity* axe of attentional functions, namely selective and divided attention (Haring et al., 2013; Jefferies et al., 2015; Maylor & Lavie, 1998; Passow et al., 2014; Stormer, Li, Heekeren, & Lindenberger, 2013) as compared to the *intensity* one (Mani, Bedwell, & Miller, 2005).

In that context, the objective of the present study was to determine to what extent decreased executive performance associated with normal aging could be influenced by a lower efficiency of some non-executive processes also prone to decline in normal aging. Here we propose that a slow-down of processing speed and weaker attentional functions may – at least partially – explain executive difficulties associated with normal aging. To comprehensively capture the relationships between these variables, we administered a large battery of executive, attentional, and processing speed tasks and we carried out mediation analyses (Baron & Kenny, 1986) in a large sample of young and older participants to determine the respective contribution of the attentional system, the processing speed, but also their interaction to the executive abilities in normal aging.

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METHOD

Our study comprised an initial sample of 104 young participants aged from 18 to 42 years and an initial sample of 71 older participants aged from 57 to 81 years. Participants were part of the Caucasian ethnicity and were all French speakers. Young people were recruited from areas inside the Province of Liège (Wallonia part of Belgium) mostly thanks to advertising in MyULiège website and thanks to word of mouth. Young participants were mostly students as well as members of the scientific community of the University of Liège (mostly outside of the Faculty of Psychology and Educational Sciences). Older people were recruited thanks to advertising in University for 3rd age standing at Liège and thanks to word of mouth. Obviously, participants were not included in the study if they were part of home retirement because of the lack of autonomy in everyday life situations that would further impact the executive functioning efficiency of older people. They all have a normal or properly corrected vision and a normal or properly corrected audition. The repartition of the highest degree level achieved by our participants according to the Belgian educative system is also shown (**Table 14** in **Supplemental Data**). All participants gave their informed consent to participate and the study was approved by the Ethics Committee of the Faculty of Psychology and Educational Sciences of the University of Liège, and was in accordance with the Declaration of Helsinki (1964). Participants had no neurological or psychiatric problem, were free of medication that could affect cognitive functioning, and reported being in good health.

Four aged people were excluded from analyses because their scores on the Mattis Dementia Rating Scale (Mattis, 1976) were equal or under 129 on 144 (Monsch et al., 1995)[2] Our final samples comprised 104 young participants and 63 older participants. Demographic data are given in **Table 1**. In order to be sure that our young and older groups did not greatly differ from each other in terms of intellectual capabilities, we decided to take the educational level as well as the Mill Hill score into account. The education variable was measured by adding the number of successful educational years since the primary school of the Belgian educative system. The Mill Hill scale (Deltour, 1993) is a verbal task assessing crystallized intelligence linked to lexical knowledge (i.e. vocabulary). This task is made of 33 items. For each item, participants had to determine, among 6 possibilities, the semantically nearest word of a given target word. The dependent variable was the total number of correct answers. We observe that the young group has a higher level of education than the older group [$t(165) = -5.71$, $p < .001$]. However, the groups also differ on the Mill Hill scale (Deltour, 1993), with an advantage for the aged participants [$t(165) = 2.21$, $p = .03$]. Taken together, these results suggest that our two groups are similar in terms of cultural background.

Table 1. Demographic data contrasting the young group and the older group.

	Young		Older	
	Raw scores	**Z-scores**	**Raw scores**	**Z-scores**
Gender (male/female)	44/60	-	38/25	-
Age (years)* **	24.68 (5.18)	-.75 (.25)	66.38 (5.83)	1.24 (.28)
Education (years)* **	14.81 (2.23)	.32 (.88)	12.68 (2.49)	-.52 (.98)
Mill Hill *	24.94 (3.83)	-.13 (.94)	26.37 (4.35)	.22 (1.06)
Mattis DRS score	-	-	138.87 (4.15)	

Note. For the raw scores, values are means and (SD) except for the distribution of gender. Z-scores were also performed through each group and means and (SD) of these z-scores inside each group are presented.

* $p < .05$; ** $p < .01$; *** $p < .001$

The whole administration of tasks was divided into two sessions of approximately 1h45 minutes each which were separated by a few days (from 1 to 15 days as a function of participants' availabilities). Participants were tested individually in a testing room free of visual or auditory disturbance.

Cognitive battery

A battery of 21 tasks was administered to assess executive, attentional, and processing speed performances of our two samples of participants. The executive processes of inhibition, shifting, updating and dual-task coordination were assessed by three tasks each. With regard to attentional functioning, the processes of selective and sustained attention were assessed by two tasks each while only one task of phasic alertness was administered. Finally, four tasks were used to determine processing speed. **Table 2** presents the considered outcomes for all tasks[3] and **Table 3** the raw mean performances in each group. We also present reliability of the executive and processing speed tasks used in **Table 15** in **Supplemental Data**. These reliability estimates have been extracted from large sample studies. As the attentional tests were taken from the well–recognized and validated battery of Zimmermann & Fimm (1994), we do not present their reliability estimates. Correlation matrices between the executive functions and processing speed measures are presented respectively in **Table 4** and **Table 5**.

Executive tests

Inhibition (Stroop, Anti-saccade, and Stop-Signal tasks): Our computerized version of the Stroop test (Stroop, 1935) consists in naming the ink color (blue, red, yellow, or green) of 144 words written in blue, red, yellow, or green. Participants had to give their answers verbally as quickly and accurately as possible; the Anti-saccade test (adapted from Roberts, Hager, & Heron, 1994) consists in 108 arrows appearing in the left or in the right of the computer screen and oriented to the left, to the right, or to the top. Before the apparition of each arrow, a blank square always appears in the opposite side of the presentation of the arrow. Participants had to give the direction of the appearing arrow thanks to the keyboard. Therefore, they had to inhibit their reflex gaze orientation to the blank square in order to detect the orientation of the arrow; the Stop-Signal task (Logan & Cowan, 1984) is divided

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into two parts. The control part is composed of 24 words belonging to living or no-living categories. For each trial, participants had to decide as quickly and accurately as possible if the word belongs to the living or no-living entities thanks to the keyboard. The test part is based on the same principle as the control part but is composed of 192 items with 25% being presented with a sound signal occurring after the presentation of the item. For these items, participants had to keep themselves from answering.

Shifting (Plus-Minus, Number-Letter, and Local-Global tasks): the Plus-Minus task (Jersild, 1927; Spector & Biederman, 1976) is divided into three parts in which participants had to react orally as quickly and accurately as possible to numbers that are verbally presented. In the first part, they had to add 3 to each number (30 in total). In the second part, they had to subtract 3 from each number (30 in total). In the third part, they had to alternate between adding and subtracting 3 from each number (31 in total); The Number–Letter task (Roger & Monsell, 1995) is divided into three parts in which a digit-letter pair (e.g., 7G) appears on the screen at each trial. In the first part, pairs (32 in total) appear only in the two bottom quadrants and participants had to make an even/odd judgment about the digit thanks to the keyboard. In the second part, pairs (32 in total) appear only in the two upper quadrants and participants had to make a vowel/consonant judgment about the letter. In the third part, pairs (128 in total) appear in pseudorandom clockwise order in the four quadrants and participants had to make an even/odd judgment when the pair was presented in the bottom quadrants and a vowel/consonant judgment when the pair was presented in the upper quadrants; the Local-Global task (Navon, 1977) is composed of 96 geometrical shapes (square, circle, triangle, cross) that are shaped by smaller squares, circles, triangles, or crosses. Participants had to orally determine the number of sides (1, 2, 3, or 4) of the global level of the geometrical shapes when they appeared in blue on the screen versus of the local level of the shapes when they appeared in red.

Updating (Tone monitoring, Letter memory, and Semantic keep track tasks): the Tone monitoring task (adapted from the Mental Counters task developed by Larson, Merritt, & Williams, 1988) is composed of high, medium, and low-pitched sounds presented in a pseudo-random order. Participants had to press the keyboard when each of these sounds was presented for the fourth time; the Letter memory task (adapted from Morris & Jones, 1990) is composed of 42 series of consonants (4, 5, 6, 7, 8, 9, or 10) visually presented in a pseudo-random order. For each trial, participants had to orally give the four latter presented consonants; the Semantic keep track task (adapted from Yntema, 1963) was composed of 27 series of words belonging to different semantic categories and presented in a pseudo-random order. For each series, participants had to orally give the last word belonging to each category (3 or 4 categories for each series).

Dual-task coordination (PASAT, Brown-Peterson, and Divided attention tasks): the Paced Auditory Serial Addition Test (PASAT; Gronwall, 1977; Gronwall & Sampson, 1974) is composed of five series of 21 digits randomly presented on the screen. Participants had to add each digit with the following one and to give the result orally. The time interval between each digit decreases from the first to the last series; in the Brown-Peterson task (Brown, 1958; Peterson & Peterson, 1959), participants had to memorize three consonants successively appearing on the screen. After a certain time delay (0, 5, 10, or 20 sec.), they had to recall the three letters in the correct order. During the time interval, participants had to repeat, in the backward order, some digit pairs that are given by the experimenter; the Divided attention task from TEA battery (Zimmermann & Fimm, 1994) was also administered and consists in the simultaneous presentation of visual and auditory information among which specific items have to be detected.

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Attentional tests

Alertness: In the Phasic alertness task from the TEA battery (Zimmermann & Fimm, 1994), participants have to react to visual stimuli preceded or not by an auditory warning signal.

Selective attention (Ocular motility and Visual scanning tasks): in the Ocular motility task from the TEA battery (Zimmermann & Fimm, 1994), a target or a neutral stimulus appears to the left or to the right of a fixation point. A target stimulus also appears in the center of the screen at irregular intervals. Participants had to react to the target stimuli; in the Visual scanning task from the TEA battery (Zimmermann & Fimm, 1994), participants had to determine whether or not a target stimulus was present in a 5X5 matrix.

Sustained attention (Visual irregularity detection and Target detection tasks): in the Visual irregularity detection task (Zimmermann & Fimm, 1994), a texture moves from a rectangle to another during 15 min. Participants had to detect irregularities in this alternation; in the Target detection task (Zimmermann & Fimm, 1994), participants had to press the keyboard each time they saw a black circle, which could appear on the screen with or without blank circles. The task was divided into two parts of 5 min.

Processing speed tests

Processing speed (Letter comparison, Tonic alertness, Articulatory speed, and Grapho-Motor speed tasks): In an adapted version of the Letter comparison task (Salthouse, 1991, 1993a; Salthouse & Babcock, 1991), participants had to decide as quickly and accurately as possible whether the two consonants of each consonant pair appearing on the screen were identical or different thanks to the keyboard; the Tonic alertness task from the TEA battery (Zimmermann & Fimm, 1994) required to respond as fast as possible to the presentation of a visual stimulus; in the Articulatory speed task, participants had to repeat a pair of words five times as quickly as possible; in the Grapho-Motor task (adapted from Salthouse & Coon, 1994), participants had to execute as many additions as possible during one minute on digits from 1 to 9 (e.g., 4+3).

Table 2. Outcomes of the executive, attentional and processing speed tasks.

Tasks	Outcomes
Stroop	Difference of the median RT between interfering (e.g., the word blue written in red) and neutral items (e.g., %%% symbols written in red)
Anti-saccade	Proportion of correctly detected arrows from the whole set of presented arrows
Stop-Signal	A diminution index was computed by subtracting the median RT of the trials of the control part from the median RT of the trials that required a response through the entire task
Plus-Minus	Difference in median RT between trials with and without shifting

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Number-Letter	Difference in median RT between trials with and without shifting
Local-Global	Difference in median RT between trials with and without alternation
Tone monitoring	Percentage of correct detections of the fourth presentation of each kind of sound
Semantic keep track	Mean percentage of correct responses
Letter memory	Percentage of consonants correctly ordered for the series comprising 5 to 10 consonants
PASAT	Percentage of correct responses
Brown-Peterson	Percentage of correctly ordered responses for the intervals of 5, 10, and 20 sec.
Didived attention	Mean RT for the visual and auditory items
Phasic alertness	Difference in median RT between trials with and without warning signal, divided by the median RT of trials for all items
Visual scanning	Median RT for the condition without target detection
Ocular motility	Difference in median RT for central and peripheral targets
Visual irregularity	Number of non-detected irregularities (omissions)
Target detection	Difference in median RT between the second and the first part of the task
Letter comparison	Median RT for similar items
Tonic alertness	Median RT for items without warning signal
Articulatory speed	Mean RT for the repetition of the three pairs of words
Grapho-Motor addition	Number of correct additions

Note. RT = reaction time.

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Table 3. Raw mean scores (standard deviations) for each executive, attentional, and processing speed measure in the two groups.

	Young	**Older**
Stroop	143.65 (70.76)	247.49 (128.4)
Anti-saccade	89.95 (9.79)	62.14 (17.18)
Stop-Signal	113.12 (152.17)	214.52 (218.36)
Plus-Minus	184.33 (161.08)	375.13 (264.71)
Number-Letter	624.99 (249.48)	1045 (443.44)
Local-Global	186.26 (138.65)	378.92 (292.53)
Tone monitoring	55.03 (22.13)	35.14 (15.36)
Semantic keep track	84.06 (6.98)	72.77 (10.57)
Letter memory	73.29 (16.47)	58.73 (14.85)
PASAT	81.92 (10.02)	61.95 (14.99)
Brown-Peterson	90.51 (8.53)	76.25 (16.6)
Didived attention	640.35 (67.36)	701.98 (90.43)
Phasic alertness (index)	0.04 (0.08)	0.04 (0.13)
Visual scanning	3552.45 (1076.29)	5244.63 (1788.91)
Ocular motility	43.3 (67)	69.24 (160.66)
Visual irregularity detections	4.15 (5.39)	7.03 (9.65)
Target detection	95.53 (39.19)	98.96 (59.74)
Letter comparison	578.97 (90.57)	771.11 (121.76)
Tonic alertness	229.56 (29.86)	289.27 (55.6)
Articulatory speed	4423.43 (811.33)	5582.76 (1177.29)
Grapho-Motor addition	51.51 (11.32)	42.56 (9.63)

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Table 4. Correlation matrices between the executive measures across the two groups.

Inhibition		Stroop	Stop-Signal	Anti-saccade
Stroop	Pearson's correlation p-value	1	.011 .897	.301*** .000
Stop-Signal	Pearson's correlation p-value		1	.289*** .000
Anti-saccade	Pearson's correlation p-value			1
Shifting		Plus-minus	Number-Letter	Global-Local
Plus-minus	Pearson's correlation p-value	1	.248** .002	.149 .068
Number-Letter	Pearson's correlation p-value		1	.175* .030
Global-Local	Pearson's correlation p-value			1
Updating		Tone monitoring	Semantic keep track	Letter memory
Tone monitoring	Pearson's correlation p-value	1	.351*** .000	.412*** .000
Semantic keep track	Pearson's correlation p-value		1	.579*** .000
Letter memory	Pearson's correlation p-value			1
Dual-task		PASAT	Brown-Peterson	Divided attention
PASAT	Pearson's correlation p-value	1	.612*** .000	.346*** .000
Brown-Peterson	Pearson's correlation p-value		1	.148 .058
Divided attention	Pearson's correlation p-value			1

Note.
* $p < .05$; ** $p < .01$; *** $p < .001$

Table 5. Correlation matrix between the four processing speed measures across the two groups.

		Letter comparison	Tonic alertness	Articulatory speed	Grapho-Motor addition
Letter comparison	Pearson's correlation p-value	1	.625*** .000	.437*** .000	.434*** .000
Tonic alertness	Pearson's correlation p-value		1	.417*** .000	.399*** .000
Articulatory speed	Pearson's correlation p-value			1	.311*** .000
Grapho-Motor addition	Pearson's correlation p-value				1

Note.

* $p < .05$; ** $p < .01$; *** $p < .001$

Composite score computation and statistical analyses

All analyses were carried out thanks to SPSS18. Since we were interested in the effect of age on executive functioning that is modulated by attentional and processing speed measures, we decided to include in mediation analyses only measures for which we observed an age effect. Therefore, in order to determine which variables were predicted by age, we carried out hierarchical multiple regression analyses by systematically controlling for the influence of gender and educational level in the first step of the model (see **Table 6**).

Since we had many measures for each assessed component (21 tasks in total), we decided to compute composite scores through both groups. Anticipating the results (**Table 6**), since all the executive measures showed an age effect, all of these variables were used for the computation of the composite scores. Theoretically based on the definitions of Baddeley (1986) and Miyake et al. (2000), we therefore created four executive composite variables with the three tasks associated with each of the following components: inhibition, shifting, updating and dual-task coordination. The executive composite scores were created according to the method proposed by Keefe et al. (2004). We first standardized the raw scores ($\frac{x- \bar{x}}{\sigma}$) by using the mean and the standard deviation of the whole sample. We also applied a "zero minus z-scores" correction on certain variables in order to get all of our measures in the same direction. Then, we averaged together the z-scores representing the same function (e.g., z-scores on Stroop, Anti-saccade, and Stop-signal tasks were averaged together to form the composite score of inhibition). Finally, these four newly created composite scores were further transformed into z-scores in order to keep each measure in a same scale.

Regarding the attentional variables, we were also initially interested in creating composite scores for the different aspects of the attentional system, theoretically based on van Zomeren and Brouwer's model (1994). Since only the Visual scanning measure was significantly impacted by age after the control of the gender and the educational level ($p < .001$, Table 8), we did not need to compute any composite score for the attentional variables. Rather, the Visual scanning variable constituted the only attentional mediator in our analyses.

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As no theoretical model allowed us to group together the various measures of processing speed, we decided to compute a composite score by including the measures that showed an age-related effect and significantly correlated to each other across our two groups. Since all the measures of processing speed were predicted by age (**Table 6**) but also correlated with each other (all $r > .30$ and all $p < .001$; see **Table 5**), we computed a single composite score with our four speed variables.

Finally, we also created an interaction variable between processing speed and attentional functioning mediators to test the hypothesis that the relationship between executive functioning and processing speed was differently impacted by the attentional function. This crossed variable was obtained by multiplying the processing speed composite score and the Visual scanning score.

We carried out mediation models, based on Baron & Kenny's recommendations (1986), with attentional functioning, processing speed, and the interaction between attentional functioning and processing speed as mediators (**Figure 1**). For example, in order to test the mediating effect of processing speed on the relation between age and inhibition, the following criteria should be met: 1) age has a significant effect on inhibition (path c); 2) age has a significant effect on processing speed (path a); 3) Processing speed has a significant effect on inhibition after having controlled for age (path b); 4) in order to get a total mediation, the effect of age on inhibition has to become non-significant after having controlled for processing speed (path c'). Otherwise, we will be in presence of partial mediation. To ensure the significance of the mediation effect, we did use the Sobel test (Sobel, 1982) whose significance threshold was corrected using the Bonferroni correction to control for the overall error rate (α/12 tests = .004). Finally, to further reinforce our results, we conducted step-by-step stepwise regressions each time we got corrected and non-corrected significant mediation effects. We used this strategy to confirm the results obtained in our mediation models. Once again, we controlled for gender and education level in a forced first bloc. Given the large number of statistical analyses, we adjusted the alpha threshold of the stepwise regressions to control for the overall error rate by setting F probability at .005 to enter a variable and at .01 to remove a variable.

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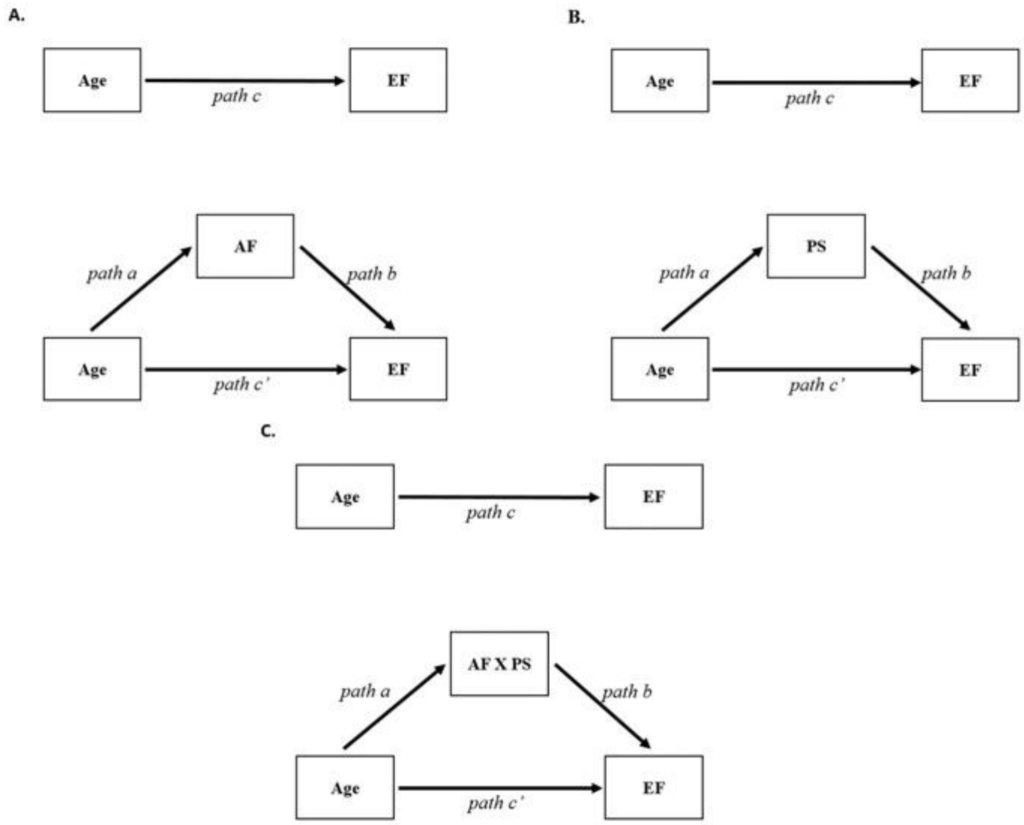

Figure 1. Illustrations of the mediation models with attentional functioning (AF, model A), processing speed (PS, model B), and the interaction between AF and PS (model C) as mediators. For each illustration, the two upper boxes with path c represent the simple model, namely the effect of age on the executive functioning. By contrast, the three-box models represent the mediation models where AF (A.), PS (B.), and AF X PS (C) respectively mediate the effect of age on the executive functioning.

EF = executive functions, namely inhibition, shifting, updating, and dual-task coordination standardized composite scores; AF = attentional functioning (namely, z-score of the Visual scanning measure); PS = processing speed standardized composite score

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RESULTS

Effect of aging

Hierarchical multiple regression analyses revealed that all executive (all $p < .001$) and processing speed (all $p < .01$) variables were predicted by age after controlling for gender and educational level. However, regarding attentional variables, only the visual scanning task ($p < .001$) was predicted by age (**Table 6**). Therefore and as indicated in the method section, we created four composite scores representing inhibition, shifting, updating, and dual-task coordination to represent our four executive functions whereas the Visual scanning task was the only variable representing the attentional functioning. Moreover, given that all processing speed measures were significantly correlated with each other [all $r > .30$ and all $p < .001$], we also computed a composite score representing processing speed (**Table 7**).

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Table 6. Hierarchical multiple regression analyses for the prediction of each function by age controlled for gender and educational level.

Dependent Variables	ΔR^2	ΔF	df	b	β	t	p
			Executive variables				
Stroop ***	.106	22.29	1, 154	-.016	-.344	-4.72	<.001
Anti-saccade ***	.408	163.83	1, 162	-.032	-.676	-12.8	<.001
Stop-Signal ***	.158	29.4	1, 155	-.02	-.423	-5.42	<.001
Plus-Minus ***	.069	14.07	1, 156	-.013	-.278	-3.75	<.001
Number-Letter ***	.261	59.69	1, 159	-.026	-.54	-7.73	<.001
Local-Global ***	.145	27.78	1, 151	-.019	-.395	-5.27	<.001
Tone monitoring ***	.116	23.98	1, 161	-.017	-.361	-4.9	<.001
Semantic keep track ***	.179	44.35	1, 163	-.021	-.448	-6.66	<.001
Letter memory ***	.092	18.76	1, 159	-.015	-.319	-4.33	<.001
PASAT ***	.278	79.32	1, 163	-.027	-.559	-8.91	<.001
Brown-Peterson ***	.116	29.56	1, 162	-.017	-.362	-5.44	<.001
Divided attention ***	.098	19.26	1, 162	-.016	-.333	-4.39	<.001
			Attentional variables				
Phasic alertness	.000	.048	1, 162	-.001	-.018	-.22	.827
Visual scanning ***	.171	39.57	1, 163	-.021	-.439	-6.29	<.001
Ocular motility	.005	.77	1, 163	-.003	-.072	-.88	.382
Visual irreg. detections	.021	3.7	1, 162	-.007	-.155	-1.92	.056
Target detection	.008	1.33	1, 162	-.005	-.095	-1.15	.251
			Processing speed variables				
Letter comparison ***	.322	95.97	1, 163	-.029	-.602	-9.8	<.001
Tonic alertness ***	.222	55.7	1 162	-.024	-.499	-7.46	<.001
Articulatory speed ***	.196	42.61	1, 155	-.022	-.472	-6.53	<.001
Grapho-Motor addition **	.05	10.29	1, 162	-.011	-.236	-3.21	.002

Note.
Analyses were performed on z-scores.
b = unstandardized coefficient of the last entered variable, namely age; β = standardized coefficient of the last entered variable, namely age; t = t-test value on the last coefficient, namely age; ΔR^2 = variation in R^2 from the step without age to the step including age as predictor; ΔF = variation in F from the step without age to the step including age as predictor; df = degrees of freedom
* $p < .05$; ** $p < .01$; *** $p < .001$

Table 7. Standardized composite scores (and SD) in each group.

	Young	Older
Inhibition ***	.54 (.56)	-.91 (.91)
Shifting ***	.49 (.57)	-.84 (1.03)
Updating ***	.46 (.78)	-.75 (.87)
Dual-task coordination ***	.5 (.65)	-.83 (.92)
Processing speed ***	.54 (.64)	-.89 (.84)
Visual scanning [a] ***	.4 (.67)	-.65 (1.11)

Note. These composite scores were created by performing the mean of the z-scores of tasks representing the same construct. Then, the five composite scores obtained were further standardized (transformed into z-scores).
[a] Visual scanning is not part of a composite score. Given that this variable was the only attentional variable predicted by age, we only took the z-score of Visual scanning as representative of the attentional system.
Comparison of young and older participants on composite scores:
* $p < .05$; ** $p < .01$; *** $p < .001$

Mediation effects

The following Tables present the meditation models with visual scanning (**Table 8**), processing speed (**Table 9**), and the interaction between visual scanning and processing speed (**Table 10**) separately considered as mediators. Gender and educational level were always entered as the first step in all of the regression models.

Results of the first mediation model (**Figure 1A**) show that, after the control of age, visual scanning performance increases the percentage of explained variance of updating [$\Delta R^2 = 7\%$, $t(162) = 4.844$, $b = .324$, $p < .001$], what is also confirmed by a significant Sobel test [$Z = -3.95$, $p < .001$]. A mediation effect of visual scanning performance for the effect of age on shifting [$\Delta R^2 = 2\%$, $t(159) = 2.53$, $b = .173$, $p = .012$] as well as on dual-task coordination [$\Delta R^2 = 1\%$, $t(162) = 2.226$, $b = .142$, $p = .027$] was also observed. However, Sobel tests on these functions do not survive the Bonferroni correction ($\alpha < .004$): for shifting [$Z = -2.37$, $p = .018$] and for dual-task coordination [$Z = -2.1$, $p = .036$]. Importantly, all these mediation effects remain partial given that the fourth step of analysis shows that age always remains significant after the control of visual scanning (all $p < .001$). By contrast, even if visual scanning increases the percentage of explained variance of inhibition [$\Delta R^2 = 1\%$, $t(161) = 2.047$, $b = .127$, $p = .042$], a Sobel test on this mediation model is not significant even when the uncorrected p threshold is taken into account [$Z = -1.95$, $p = .051$].

With regard to the second mediation model (**Figure 1B**), results show that, after the control of age, processing speed increases the percentage of explained variance for shifting [$\Delta R^2 = 7\%$, $t(159) = 4.734$, $b = .368$, $p < .001$], for updating [$\Delta R^2 = 5\%$, $t(162) = 3.836$, $b = .319$, $p < .001$], and for dual-task coordination [$\Delta R^2 = 14\%$, $t(162) = 3.326$, $b = .545$, $p < .001$].These mediating effects are further confirmed by Sobel tests for shifting [$Z = -4.19$, $p < .001$], for updating [$Z = -3.54$, $p < .001$], and for dual-task coordination [$Z = -6.22$, $p < .001$]. Once again, these results suggest that processing speed is only a partial mediator since the fourth step of analysis shows, for these three executive functions, that age remains significant

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after the control of processing speed (all $p < .001$). By contrast, processing speed increases the percentage of explained variance of inhibition [$\Delta R^2 = 1\%$, t(161) = 2.00, b = .152, p = .047] but Sobel test is not significant even when the uncorrected p threshold is taken into account [Z = -1.94, p = .052].

Finally, after the control of age, the mediator representing the interaction effect between visual scanning and processing speed variables (**Figure 1C**) increases the percentage of explained variance of inhibition [$\Delta R^2 = 1.8\%$, t(161) = -2.55, b = -.115 , p = .012], shifting [$\Delta R^2 = 3.9\%$, t(159) = -3.57, b = -.181 , $p < .001$], updating [$\Delta R^2 = 2.9\%$, t(162) = -2.86, b = -.147, p = .005] but Sobel tests are not significant even when the uncorrected p threshold is taken into account [Z = -1.4 , p =.16 for inhibition; Z = -1.56, p = .12 for shifting; Z = -1.45, p = .15 for updating]. Furthermore, the interaction between visual scanning and processing speed did not increase the percentage of explained variance of dual-task coordination [$\Delta R^2 = 0.7\%$, t(162) = -1.56, b = -.074, p = .12]. Globally, there was no significant mediation effect between age and executive functioning by the interaction between visual scanning and processing speed.

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Table 8. Mediation models of the age effect on each executive function with visual scanning as mediator.

			Inhibition				Shifting				Updating				Dual-task coordination			
			B	SE	Beta	t	B	SE	Beta	t	B	SE	Beta	t	B	SE	Beta	t
Path b	**R^2 adjusted; R^2; ΔR^2**		.101; .112; .112***				.161 ; .171 ; .171***				.195 ; .205 ; .205***				.244 ; .253 ; .253***			
	1.	Gender	.137	.152	.068	.904	-.012	.147	-.006	-.082	-.048	.143	-.024	-.336	-.053	.139	-.026	-.383
		Education	.134	.030	.341	4.531***	.162	.029	.413	5.649***	.176	.028	.448	6.309***	.195	.027	.497	7.222***
	R^2 adjusted; R^2; ΔR^2		.541; .549; .437***				.464; .474; .303***				.396; .407; .202***				.509; .518; .266***			
	2.	Gender	-.021	.109	-.010	-.190	-.139	.119	-.069	-1.175	-.160	.125	-.079	-1.281	-.181	.112	-.090	-1.613
		Education	.043	.022	.110	1.939	.086	.024	.220	3.563***	.114	.026	.289	4.442***	.124	.023	.315	5.367***
		Age	-.033	.003	-.700	-12.535***	-.028	.003	-.583	-9.593***	-.023	.003	-.476	-7.441***	-.026	.003	-.546	-9.482***
	R^2 adjusted; R^2; ΔR^2		.550; .561; .011*				.482; .494; .020*				.468; .481; .074***				.521. .533; .014*			
	3.	Gender	-.017	.108	-.008	-.156	-.134	.117	-.066	-1.147	-.149	.117	-.074	-1.269	-.176	.111	-.088	-1.588
		Education	.033	.023	.084	1.446	.073	.024	.187	2.999**	.087	.025	.221	3.534**	.112	.023	.285	4.794***
		Age	-.031	.003	-.644	-10.444***	-.024	.003	-.509	-7.657***	-.016	.003	-.334	-4.988***	-.023	.003	-.484	-7.625***
		Vis. Scan.	.127	.062	.127	2.047*	.173	.068	.169	2.528*	.324	.067	.324	4.811***	.142	.064	.142	2.226*
Path c'	**R^2 adjusted; R^2; ΔR^2**		.101; .112; .112***				.161 ; .171 ; .171***				.195 ; .205 ; .205***				.244 ; .253 ; .253***			
	1.	Gender	.137	.152	.068	.904	-.012	.147	-.006	-.082	-.048	.143	-.024	-.336	-.053	.139	-.026	-.383
		Education	.134	.030	.341	4.531***	.162	.029	.413	5.649***	.176	.028	.448	6.309***	.195	.027	.497	7.222***
	R^2 adjusted; R^2; ΔR^2		.249; .263; .151***				.295; .308; .136***				.390; .401; .196***				.353; .365; .112***			
	2.	Gender	.109	.139	.054	.782	-.037	.135	-.018	-.270	-.080	.124	-.040	-.646	-.078	.128	-.039	-.605
		Education	.076	.029	.194	2.646**	.109	.028	.278	3.903***	.110	.026	.280	4.247***	.145	.027	.370	5.450***
		Vis. scan.	.414	.072	.415	5.760***	.402	.072	.393	5.615***	.473	.065	.473	7.304***	.358	.067	.358	5.368***
	R^2 adjusted; R^2; ΔR^2		.550 ; .561 ; .298***				.482 ; .494 ; .186***				.468 ; .481 ; .080***				.521 ; .533 ; .168***			

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	3. Gender	-.017	.108	-.008	-.156		-.134	.117	-.066	-1.147		-.149	.117	-.074	-1.269		-.176	.111	-.088	-1.588
	Education	.033	.023	.084	1.446		.073	.024	.187	2.999**		.087	.025	.221	3.534**		.112	.023	.285	4.794***
	Vis. scan.	.127	.062	.127	2.047*		.173	.068	.169	2.528*		.324	.067	.324	4.811***		.142	.064	.142	2.226*
	Age	-.031	.003	-.644	-10.444***		-.024	.003	-.509	-7.657***		-.016	.003	-.334	-4.988***		-.023	.003	-.484	-7.625***

Note. Steps 3 (path b) & 4 (path c') required by Baron & Kenny (1986) for mediation models. ΔR^2 = variation in R^2 from the previous to the present step; B = unstandardized coefficient; SE = standard error; Beta = standardized coefficient; t = t-test value on the last coefficient; Vis. Scan. = Visual Scanning.

* $p < .05$; ** $p < .01$; *** $p < .001$

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Table 9. Mediation models of the age effect on each executive function with processing speed as mediator.

		Inhibition				**Shifting**				**Updating**				**Dual-task coordination**			
		B	**SE**	**Beta**	**t**	**B**	**SE**	**Beta**	**t**	**B**	**SE**	**Beta**	**t**	**B**	**SE**	**Beta**	**t**
Path b	**R^2 adjusted; R^2; ΔR^2**	.101; .112; .112***				.161 ; .171 ; .171***				.195 ; .205 ; .205***				.244 ; .253 ; .253***			
	1. Gender	.137	.152	.068	.904	-.012	.147	-.006	-.082	-.048	.143	-.024	-.336	-.053	.139	-.026	-.383
	Education	.134	.030	.341	4.531***	.162	.029	.413	5.649***	.176	.028	.448	6.309***	.195	.027	.497	7.222***
	R^2 adjusted; R^2; ΔR^2	.541; .549; .437***				.464; .474; .303***				.396; .407; .202***				.509; .518; .266***			
	2. Gender	-.021	.109	-.010	-.190	-.139	.119	-.069	-1.175	-.160	.125	-.079	-1.281	-.181	.112	-.090	-1.613
	Education	.043	.022	.110	1.939	.086	.024	.220	3.563***	.114	.026	.289	4.442***	.124	.023	.315	5.367***
	Age	-.033	.003	-.700	-12.535***	-.028	.003	-.583	-9.593***	-.023	.003	-.476	-7.441***	-.026	.003	-.546	-9.482***
	R^2 adjusted; R^2; ΔR^2	.549; .560; .011*				.527; .539; .065***				.443; .456; .049***				.654; .663; .144***			
	3. Gender	.006	.109	.003	.054	-.084	.112	-.042	-.751	-.111	.120	-.055	-.926	-.099	.095	-.049	-1.042
	Education	.028	.023	.072	1.218	.050	.024	.127	2.081*	.081	.026	.207	3.133**	.069	.020	.174	3.352**
	Age	-.029	.003	-.611	-8.64***	-.018	.003	-.370	-5.107***	-.014	.004	-.289	-3.679***	-.011	.003	-.226	-3.662***
	Speed	.152	.076	.150	2.001*	.368	.078	.363	4.734***	.319	.083	.319	3.836***	.545	.065	.545	8.326***
Path c'	**R^2 adjusted; R^2; ΔR^2**	.101; .112; .112***				.161 ; .171 ; .171***				.195 ; .205 ; .205***				.244 ; .253 ; .253***			
	1. Gender	.137	.152	.068	.904	-.012	.147	-.006	-.082	-.048	.143	-.024	-.336	-.053	.139	-.026	-.383
	Education	.134	.030	.341	4.531***	.162	.029	.413	5.649***	.176	.028	.448	6.309***	.195	.027	.497	7.222***
	R^2 adjusted; R^2; ΔR^2	.344; .356; .244***				.453; .463; .292***				.400; .411; .206***				.628; .635; .382***			
	2. Gender	.162	.130	.080	1.247	.003	.119	.001	.023	-.041	.123	-.020	-.334	-.044	.097	-.022	-.450
	Education	.037	.028	.094	1.305	.055	.026	.141	2.150*	.085	.027	.217	3.167**	.072	.021	.182	3.379**
	Speed	.561	.072	.554	7.839***	.613	.066	.605	9.329***	.509	.068	.509	7.539***	.694	.053	.694	13.058***
	R^2 adjusted; R^2; ΔR^2	.549; .560; .204***				.527 ; .539 ; .076***				.443 ; .456 ; .045***				.654 ; .663 ; .028***			

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	3.	Gender	.006	.109	.003	.054		-.084	.112	-.042	-.751		-.111	.120	-.055	-.926		-.099	.095	-.049	-1.042
		Education	.028	.023	.072	1.218		.050	.024	.127	2.081*		.081	.026	.207	3.133**		.069	.020	.174	3.352**
		Speed	.152	.076	.150	2.001*		.368	.078	.363	4.734***		.319	.083	.319	3.836***		.545	.065	.545	8.326***
		Age	-.029	.003	-.611	-8.64***		-.018	.003	-.370	-5.107***		-.014	.004	-.289	-3.679***		-.011	.003	-.226	-3.662***

Note. Steps 3 (path b) & 4 (path c') required by Baron & Kenny (1986) for mediation models. ΔR^2 = variation in R^2 from the previous to the present step; B = unstandardized coefficient; SE = standard error; Beta = standardized coefficient; t = t-test value on the last coefficient; Speed = Processing speed.
* $p < .05$; ** $p < .01$; *** $p < .001$

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Table 10. Mediation models of age effect on each executive function with the interaction between visual scanning and processing speed as mediator.

		Inhibition				**Shifting**				**Updating**				**Dual-task coordination**			
		B	**SE**	**Beta**	**t**	**B**	**SE**	**Beta**	**t**	**B**	**SE**	**Beta**	**t**	**B**	**SE**	**Beta**	**t**
Path b	**R^2 adjusted; R^2; ΔR^2**	.101; .112; .112***				.161 ; .171 ; .171***				.195 ; .205 ; .205***				.244 ; .253 ; .253***			
	1. Gender	.137	.152	.068	.904	-.012	.147	-.006	-.082	-.048	.143	-.024	-.336	-.053	.139	-.026	-.383
	Education	.134	.030	.341	4.531***	.162	.029	.413	5.649***	.176	.028	.448	6.309***	.195	.027	.497	7.222***
	R^2 adjusted; R^2; ΔR^2	.541; .549; .437***				.464; .474; .303***				.396; .407; .202***				.509; .518; .266***			
	2. Gender	-.021	.109	-.010	-.190	-.139	.119	-.069	-1.175	-.160	.125	-.079	-1.281	-.181	.112	-.090	-1.613
	Education	.043	.022	.110	1.939	.086	.024	.220	3.563***	.114	.026	.289	4.442***	.124	.023	.315	5.367***
	Age	-.033	.003	-.700	-12.535***	-.028	.003	-.582	-9.593***	-.023	.003	-.476	-7.441***	-.026	.003	-.546	-9.482***
	R^2 adjusted; R^2; ΔR^2	.556; .567; .018*				.501; .513; .039***				.421; .435; .029**				.514; .525; .007			
	3. Gender	-.03	.107	-.015	-.275	-.156	.114	-.078	-1.365	-.17	.122	-.084	-1.393	-.186	.112	-.093	-1.666
	Education	.036	.022	.092	1.628	.077	.024	.196	3.262**	.104	.025	.266	4.139***	.119	.023	.303	5.149***
	Age	-.032	.003	-.677	-12.181***	-.026	.003	-.552	-9.326***	-.021	.003	-.447	-7.058***	-.025	.003	-.532	-9.159***
	Vis. Scan. X Speed P.	-.115	.045	-.136	-2.551*	-.181	.051	-.202	-3.565***	-.147	.052	-.174	-2.861**	-.074	.047	-.087	-1.562
Path c'	**R^2 adjusted; R^2; ΔR^2**	.101; .112; .112***				.161 ; .171 ; .171***				.195 ; .205 ; .205***				.244 ; .253 ; .253***			
	1. Gender	.137	.152	.068	.904	-.012	.147	-.006	-.082	-.048	.143	-.024	-.336	-.053	.139	-.026	-.383
	Education	.134	.030	.341	4.531***	.162	.029	.413	5.649***	.176	.028	.448	6.309***	.195	.027	.497	7.222***
	R^2 adjusted; R^2; ΔR^2	.152; .167; .055**				.232; .247; .075***				.248; .262; .056**				.266; .28; .027*			
	2. Gender	.113	.148	.056	.764	-.044	.141	-.022	-.314	-.072	.138	-.036	-.518	-.069	.137	-.034	-.508
	Education	.116	.029	.296	3.973***	.143	.028	.366	5.157***	.158	.027	.402	5.76***	.183	.027	.465	6.749***
	Vis. Scan. X Speed	-.202	.062	-.24	-3.285**	-.249	.062	-.278	-3.992***	-.205	.058	-.242	-3.528**	-.142	.057	-.168	-2.477*

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	R^2 adjusted; R^2; ΔR^2	.556; .567; .399***					.501; .513; .266***					.421; .435; .174***					.514; .525; .246***			
	3. Gender	-.03	.107	-.015	-.275		-.156	.114	-.078	-1.365		-.17	.122	-.084	-1.393		-.186	.112	-.093	-1.666
	Education	.036	.022	.092	1.628		.077	.024	.196	3.262**		.104	.025	.266	4.139***		.119	.023	.303	5.149***
	Vis. Scan. X Speed	-.115	-.045	-.136	-2.551*		-.181	.051	-.202	-3.565***		-.147	.052	-.174	-2.861**		-.074	.047	-.087	-1.562
	Age	-.032	.003	-.677	-12.181***		-.026	.003	-.552	-9.326***		-.021	.003	-.447	-7.058***		-.025	.003	-.532	-9.159***

Note. Steps 3 (path b) & 4 (path c') required by Baron & Kenny (1986) for mediation models. ΔR^2 = variation in R^2 from the previous to the present step; B = unstandardized coefficient; SE = standard error; Beta = standardized coefficient; t = t-test value on the last coefficient; Vis. Scan. = Visual Scanning; Speed = Processing speed.

* $p < .05$; ** $p < .01$; *** $p < .001$

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Confirmatory stepwise analyses

In order to fully support these results, we carried out confirmatory stepwise regression analyses (**Table 11**) for the corrected and non-corrected significant mediation effects. The results show that visual scanning increases the explained variance of updating beyond the effect of age [$\Delta R^2 = .074$. $\beta = .324$. $p < .001$] but not for the other executive functions. Regarding processing speed, this variable adds supplementary explained variance to shifting once age is taken into account [$\Delta R^2 = .065$. $\beta = .363$. $p < .001$]. Interestingly, processing speed is chosen as the first explicative variable for updating [$\Delta R^2 = .206$. $\beta = .319$. $p < .001$] and dual-task coordination [$\Delta R^2 = .382$. $\beta = .545$. $p < .001$] before age, showing again the contribution of this variable to explained variance.

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Table 11. Confirmatory stepwise analyses relative to the Visual scanning and processing speed.

		Shifting					Updating					Dual-task coordination			
		B	SE	Beta	t		B	SE	Beta	t		B	SE	Beta	t
Visual scanning	**R^2 adjusted; R^2; ΔR^2**	.161 ; .171 ; .171***				**R^2 adjusted; R^2; ΔR^2**	.195 ; .205 ; .205***				**R^2 adjusted; R^2; ΔR^2**	.244 ; .253 ; .253***			
	1. Gender	-.012	.147	-.006	-.082	1. Gender	-.048	.143	-.024	-.336	1. Gender	-.053	.139	-.026	-.383
	Education	.162	.029	.413	5.649***	Education	.176	.028	.448	6.309***	Education	.195	.027	.497	7.222***
	R^2 adjusted; R^2; ΔR^2	.464; .474; .303***				**R^2 adjusted; R^2; ΔR^2**	.396; .407; .202***				**R^2 adjusted; R^2; ΔR^2**	.509; .518; .266***			
	2. Gender	-.139	.119	-.069	-1.175	2. Gender	-.160	.125	-.079	-1.281	2. Gender	-.181	.112	-.090	-1.613
	Education	.086	.024	.220	3.563***	Education	.114	.026	.289	4.442***	Education	.124	.023	.315	5.367***
	Age	-.028	.003	-.583	-9.593***	Age	-.023	.003	-.476	-7.441***	Age	-.026	.003	-.546	-9.482***
						R^2 adjusted; R^2; ΔR^2	.468; .481; .074***								
						3. Gender	-.149	.117	-.074	-1.269					
						Education	.087	.025	.221	3.534**					
						Age	-.016	.003	-.334	-4.988***					
						Vis. Scan.	.324	.067	.324	4.811***					
Processing speed	**R^2 adjusted; R^2; ΔR^2**	.161 ; .171 ; .171***				**R^2 adjusted; R^2; ΔR^2**	.195 ; .205 ; .205***				**R^2 adjusted; R^2; ΔR^2**	.244 ; .253 ; .253***			
	1. Gender	-.012	.147	-.006	-.082	1. Gender	-.048	.143	-.024	-.336	1. Gender	-.053	.139	-.026	-.383
	Education	.162	.029	.413	5.649***	Education	.176	.028	.448	6.309***	Education	.195	.027	.497	7.222***
	R^2 adjusted; R^2; ΔR^2	.464; .474; .303***				**R^2 adjusted; R^2; ΔR^2**	.400; .411; .206***				**R^2 adjusted; R^2; ΔR^2**	.628; .635; .382***			
	2. Gender	-.139	.119	-.069	-1.175	2. Gender	-.041	.123	-.020	-.334	2. Gender	-.044	.097	-.022	-.450
	Education	.086	.024	.220	3.563***	Education	.085	.027	.217	3.167**	Education	.072	.021	.182	3.379**
	Age	-.028	.003	-.582	-9.593***	Speed	.509	.068	.509	7.539***	Speed	.694	.053	.694	13.058***
	R^2 adjusted; R^2; ΔR^2	.527 ; .539 ; .065***				**R^2 adjusted; R^2; ΔR^2**	.443 ; .456 ; .045***				**R^2 adjusted; R^2; ΔR^2**	.654 ; .663 ; .028***			

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	3.	Gender	-.084	.112	-.042	-.751	3.	Gender	-.111	.120	-.055	-.926	3.	Gender	-.099	.095	-.049	-1.042
		Education	.050	.024	.127	2.081*		Education	.081	.026	.207	3.133**		Education	.069	.020	.174	3.352**
		Age	-.018	.003	-.370	-5.107***		Speed	.319	.083	.319	3.836***		Speed	.545	.065	.545	8.326***
		Speed	.368	.078	.363	4.734***		Age	-.014	.004	-.289	-3.679***		Age	-.011	.003	-.226	-3.662***

Note. ΔR^2 = variation in R^2 from the previous to the present step; B = unstandardized coefficient; SE = standard error; Beta = standardized coefficient; t = t-test value on the last coefficient; Vis. Scan. = Visual Scanning; Speed = Processing speed.
* $p < .05$; ** $p < .01$; *** $p < .001$

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Exploratory analyses: inhibition as a mediator?

We finally tentatively explored a *mediation by inhibition hypothesis* by carrying out *a posteriori* mediation analyses (see **Table 12**) of age by the function of inhibition on the three other executive functions – shifting, updating, and dual-task coordination. We found that, after the control of age, inhibition increases the percentage of explained variance of shifting [ΔR^2 = 1.8%, t(158) = 2.362, b = .206, p = .019], updating [ΔR^2 = 2%, t(161) = 2.478, b = .218, p = .014], and dual-task coordination [ΔR^2 = 2%, t(161) = 2.811, b = .224, p = .006]. These results are further supported by significant Sobel tests [Z = -2.31, p = .02 for shifting; Z = -2.41, p = .016 for updating; Z = -2.7, p = .007 for dual-task coordination] but only for uncorrected p values. As for the other mediators, these exploratory results suggest that inhibition would be only a partial mediator since the fourth step of analysis shows that age remains significant after the control of inhibition (all $p < .001$). However, confirmatory step-by-step stepwise analyses performed for these mediation effects did not retain inhibition as a predictor of the other executive functions once gender, educational level and age were taken into account (see **Table 13**).

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Table 12. Mediation models of the age effect on shifting, updating, and dual-task coordination with inhibition as mediator.

			Shifting				Updating				Dual-task coordination			
			B	SE	Beta	t	B	SE	Beta	t	B	SE	Beta	t
Path b	**R^2 adjusted; R^2; ΔR^2**		.160 ; .170 ; .170***				.200 ; .210 ; .210***				.244 ; .253 ; .253***			
	1.	Gender	-.018	.149	-.009	-.123	-.030	.143	-.015	-.208	-.048	.140	-.024	-.344
		Education	.161	.029	.410	5.583***	.179	.028	.455	6.398***	.196	.027	.498	7.207***
	R^2 adjusted; R^2; ΔR^2		.463; .472; .303***				.405; .416; .206***				.512; .520; .267***			
	2.	Gender	-.140	.119	-.069	-1.171	-.138	.124	-.069	-1.112	-.172	.113	-.085	-1.521
		Education	.086	.024	.220	3.542**	.116	.025	.296	4.570***	.125	.023	.317	5.405***
		Age	-.028	.003	-.581	-9.550***	-.023	.003	-.480	-7.560***	-.026	.003	-.547	-9.503***
	R^2 adjusted; R^2; ΔR^2		.478; .490; .018*				.423; .437; .021*				.532; .543; .022**			
	3.	Gender	-.146	.118	-.072	-1.238	-.134	.123	-.066	-1.092	-.167	.111	-.083	-1.511
		Education	.077	.024	.198	3.193**	.107	.025	.272	4.216***	.115	.023	.293	5.033***
		Age	-.021	.004	-.435	-5.051***	-.016	.004	-.328	-3.733***	-.019	.004	-.391	-4.941***
		Inhibition	.206	.087	.205	2.362*	.218	.088	.218	2.478*	.224	.080	.223	2.811**
Path c'	**R^2 adjusted; R^2; ΔR^2**		.160 ; .170 ; .170***				.200 ; .210 ; .210***				.244 ; .253 ; .253***			
	1.	Gender	-.018	.149	-.009	-.123	-.030	.143	-.015	-.208	-.048	.140	-.024	-.344
		Education	.161	.029	.410	5.583***	.179	.028	.455	6.398***	.196	.027	.498	7.207***
	R^2 adjusted; R^2; ΔR^2		.397; .408; .238***				.377; .389; .179***				.464; .474; .220***			
	2.	Gender	-.111	.126	-.055	-.878	-.091	.127	-.045	-.721	-.117	.118	-.058	-.989
		Education	.091	.026	.233	3.524**	.118	.026	.301	4.531***	.129	.024	.328	5.310***
		Inhibition	.521	.065	.518	8.002***	.449	.065	.449	6.884***	.500	.061	.498	8.237***
	R^2 adjusted; R^2; ΔR^2		.478 ; .490 ; .082***				.423 ; .437 ; .049***				.532 ; .543 ; .069***			
	3.	Gender	-.146	.118	-.072	-1.238	-.134	.123	-.066	-1.092	-.167	.111	-.083	-1.511
		Education	.077	.024	.198	3.193**	.107	.025	.272	4.216***	.115	.023	.293	5.033***
		Inhibition	.206	.087	.205	2.362*	.218	.088	.218	2.478*	.224	.080	.223	2.811**

	Age		-.021	.004	-.435	-5.051***		-.016	.004	-.328	-3.733***		-.019	.004	-.391	-4.941**

Note. Steps 3 (path b) & 4 (path c') required by Baron & Kenny (1986) for mediation models. ΔR^2 = variation in R^2 from the previous to the present step; B = unstandardized coefficient; SE = standard error; Beta = standardized coefficient; t = t-test value on the last coefficient.
* p < .05; ** p < .01; *** p < .001

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Table 13. Confirmatory stepwise analyses relative to the mediation by inhibition hypothesis.

		Shifting					Updating					Dual-task coordination			
		B	**SE**	**Beta**	**t**		**B**	**SE**	**Beta**	**t**		**B**	**SE**	**Beta**	**t**
Inhibition	**R^2 adjusted; R^2; ΔR^2**	.160 ; .170 ; .170***				**R^2 adjusted; R^2; ΔR^2**	.200 ; .210 ; .210***				**R^2 adjusted; R^2; ΔR^2**	.244 ; .253 ; .253***			
	1. Gender	-.018	.149	-.009	-.123	1. Gender	-.030	.143	-.015	-.208	1. Gender	-.048	.140	-.024	-.344
	Education	.161	.029	.410	5.583***	Education	.179	.028	.455	6.398***	Education	.195	.027	.498	7.207***
	R^2 adjusted; R^2; ΔR^2	.463; .472; .303***				**R^2 adjusted; R^2; ΔR^2**	.405; .416; .206***				**R^2 adjusted; R^2; ΔR^2**	.512; .520; .267***			
	2. Gender	-.140	.119	-.069	-1.171	2. Gender	-.138	.124	-.069	-1.112	2. Gender	-.172	.113	-.085	-1.521
	Education	.086	.024	.220	3.542**	Education	.116	.025	.296	4.570***	Education	.124	.023	.317	5.405***
	Age	-.028	.003	-.581	-9.550***	Age	-.023	.003	-.480	-7.560***	Age	-.026	.003	-.547	-9.503***

Note. ΔR^2 = variation in R^2 from the previous to the present step; B = unstandardized coefficient; SE = standard error; Beta = standardized coefficient; t = t-test value on the last coefficient;
* $p < .05$; ** $p < .01$; *** $p < .001$

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DISCUSSION

The aim of this study was to determine the potential mediating effect of processing speed and attentional processes on age-related effects in executive functioning. Accordingly, we administered a large battery of executive, attentional and processing speed tasks. We observed age effects on the Visual scanning attentional task, and on all executive and processing speed measures. We also evidenced a partial mediation effect of visual scanning abilities on updating performance as well as a partial effect of processing speed on shifting, updating and dual-task performance. These results were also supported by confirmatory stepwise analyses. However, processing speed and attentional factors were not mediators of the age effect on inhibitory abilities, and an exploratory analysis seems to indicate that inhibition could also be a mediator for the three remaining executive variables. Nevertheless, these *mediation by inhibition* effects were not further supported by confirmatory stepwise analyses.

Age effects on executive, processing speed and attentional tasks

Our results are in agreement with previous data by showing that all executive variables were predicted by age (Collette & Salmon, 2014; Crawford, Bryan, Luszcz, Obonsawin, & Stewart, 2000; Salthouse et al., 2003; West, 1996; West, 2000). Nevertheless, some studies indicated that not all aspects of executive functioning decrease with advancing age, with a preservation of automatic inhibitory processes and specific alternation processes in shifting task (e.g., Hogge et al., 2008; Kray et al., 2004). The generalized age-related effect across tasks observed here can be explained by the use of only controlled inhibitory tasks and shifting tasks that were not designed to disentangle local and global alternation processes.

Likewise, and as it could have been expected from several previous studies (Albinet et al., 2012; Cona et al., 2013; Manard et al., 2014; Salthouse, 1992; Salthouse, 1993; Salthouse, 1994a; Salthouse, 1994b; Salthouse, 1996; Salthouse & Babcock, 1991; Salthouse & Meinz, 1995; Salthouse, 2000; Salthouse et al., 2000), all processing speed variables were predicted by age. Salthouse proposed that perceptual speed is more involved in the relationship between age and cognition than motor speed (Salthouse, 1993; Salthouse, 1994b). We consider tasks administrated here as involving perceptual speed as they all require processing auditory or visual information before producing the response.

With regard to attentional functions, we found that only performance on the Visual scanning task, requiring selective attention abilities, was significantly predicted by age. It is somewhat consistent with studies having shown an age effect on selective attention (Haring et al., 2013; Jefferies et al., 2015; Maylor & Lavie, 1998; Passow et al., 2014; Stormer et al., 2013) and no effect on sustained attention (Quigley, Andersen, & Müller, 2012). Nevertheless, it is not in agreement with studies demonstrating an age effect on alertness (Festa-Martino, Ott, & Heindel, 2004; Pate, Margolin, Friedrich, & Bentley, 1994) and sustained attention (Mani et al., 2005). However, attentional abilities remain rarely explored with a large range of tasks in older people.

Here, we decided to use van Zomeren and Brouwer's model (1994) in order to fully assess attention in its different components. This model is still greatly used in the clinical practice, allowing to apply a well-recognized and validated battery of attention tasks (Zimmermann & Fimm, 1994). Nonetheless, we cannot exclude the possibility that the use of other attention models, such as the one of Corbetta and Shulman (2002) but also the one of the three attention networks based on Posner and Petersen (1990), could have led to slightly different results. For example, administering tasks assessing the dorsal attention network and the ventral attention networks (Corbetta & Shulman, 2002; Corbetta et al., 2008) would have maybe allowed evidencing some age effect on goal-directed attention *VS* stimulus-driven attention. Indeed, as aging is well recognized to primarily impact executive functions (De Beni & Borella, 2015; Podell et al., 2012; Salthouse et al., 2003; West, 2000), it would be interesting to test whether the more controlled top-down attention (dorsal attention network) is more diminished than the bottom-up attention (ventral attention network) during normal aging. Likewise, we cannot exclude that different results could have emerged if we were using the Attention Network Test (ANT, Fan et al., 2002). However, the few studies having used the so-called[4] Attention Network Test (ANT, Fan et al., 2002) to simultaneously assess the processes of alerting, orienting, and executive attention have shown a larger negative age effect on the executive network than on the two other networks (Mahoney et al., 2011; Lu et al., 2016; Zhou et al., 2011). These results can be considered as relatively similar to those obtained here with separate attentional and executive tasks. Similarly, the investigation of canonical resting-states brain networks in young and older people showed that the executive control network (ECN) was the most affected by age, followed by the dorsal attention network (DAN) (Zhang et al., 2014). Therefore, it seems that attentional functions decrease to a lesser extent with age as compared to executive functions.

The absence of age-related effect on our attentional tasks could also be related to the control of educational level. Indeed, previous studies that showed an attentional decrease in older people did not systematically take the educational level into account (Festa-Martino et al., 2004; Haring et al., 2013; Jefferies et al., 2015; Mani et al., 2005; Pate et al., 1994; Maylor & Lavie, 1998; Passow et al., 2014) while educational level has been related to various measures assessing cognition in aging (Meguro et al., 2001; Springer, McIntosh, Winocur, & Grady, 2005). Therefore, it is possible that the level at which people are educated is correlated with attentional functions that are particularly needed in school learning (Posner & Rothbart, 2014). Consequently, our control for the educational level may challenge the previously found age effect on attentional variables.

Correlations between the executive tasks

Globally, we have some evidence of convergent validity. For each executive function, there are maximum two tasks that do not significantly correlate with each other while the other are well correlated. However, our methodology was more theorically-driven than data-driven. Indeed, we decided to perform these grouping of task theoretically based on Miyake's model (2000). Nonetheless, there are very obvious reasons to explain the lack of correlations between certain tasks supposed to tap the same executive function.

In a theoretical point of view, Harnishfeger (1995) distinguished between intentional *VS*. non-intentional inhibition but also between cognitive *VS*. behavioral inhibition. In agreement with this conception, many studies suggest the existence of different inhibitory mechanisms (e.g. Borella et al., 2009; Hamilton & Martin, 2005; Nassauer & Halperin, 2003; Rush, Barch, & Braver, 2006). For example, Borella et al. (2009) evidence weak correlation between inhibition indices of two version of a same inhibition task as well as between different inhibition tasks. Nassauer & Halperin (2003) evidenced some difference in performances between perceptive *VS*. motor inhibition in young people. Likewise, Rush et al. (2006) evidenced weak correlation in young and older people between different inhibitory tasks comprising a Stroop task and a Stop-Signal task. Given the cognitive nature of the Stroop task and the motor nature of the Stop-Signal task, our lack of correlation may suggest these tasks would assess different aspects of the inhibition function (Rush et al., 2006). As mentioned in the introduction, Borella et al. (2011) failed to find correlation between their two inhibition measures (interference index and negative priming index). This finding pleads in favor of the assumption of multidimensional inhibition (Borella et al., 2008, 2009; de Ribaupierre, 2001; de Ribaupierre et al., 2003).

In a same vein, the lack of correlation between two shifting tasks could be due to the fact that they bear on different mechanisms. Indeed, the required alternation inside the Plus-Minus task is fully predictable and therefore is initiated in an endogenous way while the required alternation inside the Global-Local task is not predictable at all and is therefore initiated in an exogenous way (Salmon et al., 2010).

Likewise, Fournier, Larigauderie, and Ganoac'h (2004) evidenced different processes of dual-task coordination : 1) the ability to simultaneously maintain and manipulate visuo-spatial information; 2) the ability to simultaneously maintain and manipulate verbal information; 3) the ability to coordinate different types of processing which do not need any storage. Given that the Brown-Petersen is a very good example of task requiring to simultaneously maintain and manipulate verbal information while the Divided attention task requires coordination without any storage, the lack of significant correlation between these two tasks is understandable.

Attention and processing speed as mediators of the age-related decline on executive functioning

The attentional variable "visual scanning" significantly mediated the effect of age on the updating function. However, this mediation effect was a partial one, meaning that age remains a significant predictor of updating despite the presence of that mediator. Therefore, we can assume that the decrease in updating efficiency in older people is primarily explained by age but also by selective attention. In the updating tasks, participants have to continuously switch their attentional focus to the most recently presented information, a process requiring selective attention abilities very close to the ones necessary to sequentially inspect the matrix of stimuli in the Visual scanning task. However, no mediator effect of that attentional variable was observed for the executive functions of shifting, inhibition and dual-task coordination. As a whole, these results do not agree with our initial hypothesis that attentional efficiency would influence executive performance in normal aging. This hypothesis was based on a neuroimaging study claiming the existence of common neural substrates between executive and attentional processes (Collette et al., 2005) and a recent confirmatory factor analysis indicating that attentional processes could in part drive the commonality of executive functions (Hogge, submitted). Actually, the absence of mediation effect by visual scanning seems logical for dual-task coordination that requires to separate one's attentional resources between different cognitive activities. This notion is just opposed to the function of selective attention in van Zomeren and Brouwer's model (1994). Likewise, shifting has already been considered as a complementary component of divided attention (van Zomeren & Brouwer, 1994). Indeed, shifting can intervene as soon as people have to switch their attention between several activities they are engaged in and they are not actually able to simultaneously manage. By contrast, the absence of mediation effect of age by visual scanning on inhibition is more difficult to explain, as selective attention and inhibition are often considered to act conjointly to select target information and suppress irrelevant one (Neill, Valdes, & Terry, 1995). As the Visual scanning task mainly assesses the external orientation of attention and does not require any need of inhibition, we therefore suggest that the task could not be the most adequate to explore a mediation effect of age by selective attention on inhibition.

However, two alternative hypotheses have to be considered to explain the lack of mediation effect by attention: the *mediation by inhibition hypothesis* and the *dedifferentiation* *hypothesis.* Regarding the *mediation by inhibition hypothesis*, Miyake et al. (2000; see also Friedman et al., 2008; Friedman, Miyake, Robinson, & Hewitt, 2011) proposed that all executive functions involve an inhibitory capacity to suppress task-irrelevant distractors, which is considered to be a basic unit of working memory or executive functioning by certain authors (e.g., Dempster & Corkill, 1999; Zacks, Hasher, & Radvansky, 1996) but also as a ‘‘fundamental regulatory mechanisms’’ (Hasher, Lustig, & Zacks, 2007) of cognition. Otherwise, inhibition is considered as one of the first cognitive processes to decline with age (Hasher & Zacks, 1988; Persad, Abeles, Zacks, & Denburg, 2002; Radvansky, Zacks, & Hasher, 2005). Hasher & Zacks (1988) proposed that a reduction in inhibition would be a major source of decrement in working memory of aging people. It is the reason why some authors assumed that it could explain some deficits in other cognitive tasks (e.g., Borella, Carretti, Cornoldi, & De Beni, 2007; Borella, Carretti, & Mammarella, 2006; Persad, Abeles, Zacks, & Denburg, 2002). Consequently, inhibition could be a mediator variable between age and executive abilities. We assessed that hypothesis in exploratory *post-hoc* analyses and evidenced a partial mediation of the age effect by inhibition on the three other executive functions. These results are in agreement with studies explaining the common activation of executive functions by a certain implication of inhibition mechanisms which allow people suppressing irrelevant distracting stimuli and keeping focused on the current task goals (Miyake et al., 2000; Wojciulik & Kanwisher, 1999). However, as these exploratory results were not confirmed by stepwise analyses, further studies are necessary to confirm the potential role of inhibition as a mediator for executive efficiency in aging.

Otherwise, only young participants were included in studies having shown the influence of attentional processes on the executive functions (Collette et al., 2005; Hogge, submitted) while the organization of executive functioning seems to be modified in aging. Indeed, some data indicates that aging is associated with a *dedifferentiation* of the executive processes (de Frias et al., 2006; Delaloye et al., 2009, Hedden & Yoon, 2006) leading to a grouping of factors (for example, flexibility and inhibition, de Frias et al., 2006; flexibility and updating, Adrover-Roig, Sesé, Barcelo, & Palmer, 2012). Moreover, there would also exist a reduction in the distinctiveness of neural representations, as well as changes in the ability of different neural regions to communicate with each other (Goh, 2011). On this basis, we can tentatively propose that the more diffuse cognitive and brain representations in aging lead to changes in the relationships between attentional and executive variables by comparison with young participants. This interpretation obviously needs to be specifically explored in future studies.

According to our initial hypothesis, the processing speed variable significantly partially mediated the effect of age on shifting, updating and dual-task coordination. These results are in great agreement with the literature showing a large influence of the slow-down of processing speed on different aspects of cognition in aging (Albinet et al., 2012; Cona et al., 2013; Manard et al., 2014; Salthouse, 1992; Salthouse, 1993; Salthouse, 1994a, Salthouse, 1994b; Salthouse, 1996; Salthouse & Babcock, 1991; Salthouse & Meinz, 1995; Salthouse, 2000; Salthouse et al., 2000). Moreover, processing speed was chosen as the first explicative variable for updating and dual-task coordination in stepwise analyses. These results are particularly interesting given that outcome measures for updating and dual-task coordination were all except one expressed in other measures than reaction time. This suggests that processing speed is at least as useful in predicting performance in terms of level of accuracy as in terms of reaction time. However, our procedure does not allow us to disentangle on which mechanisms processing speed acts to mediate the effect of age. For example, it is possible that older participants meet certain difficulties to perform adequately all required cognitive operations due to the paced nature of the tasks (*a limited time mechanism)* or that the processed information decreases in availability over time (due to longer response times, *a simultaneity mechanism*) (see Salthouse, 1996).

Finally, if the mediating effect of processing speed on shifting (Kray & Lindenberger, 2000; Salthouse et al., 2000), updating (Fisk & Sharp, 2004), and dual-task coordination (Baddeley, 2001) is consistent with the literature, our results are far from the common findings according to which the control of processing speed dramatically decreases the effect of age on inhibition (de Ribaupierre, 1995; Hogge et al., 2008; Salthouse, 1992; Salthouse & Meinz, 1995; Verhaegen & Cerella, 2002; Verhaeghen & De Meersman, 1998). As mentioned in the Method, it is also the reason why many authors (de Frias et al., 2006; Delaloye et al., 2009; Ludwig et al., 2010) rightly prefer to adopt relative scores that control for individual differences – namely, baseline *processing speed* individual difference – in their analyses instead of simple difference score. However, since we were interested in the mediation effect of processing speed between age and inhibition, we used simple difference score (MacLeod, 1991). Therefore, we would say that even without computing interfering score controlled for baseline processing speed, we did not find any mediation effect of processing speed between age and inhibition. If we had controlled for baseline processing speed in our interference scores, our absence of result could have been attributed to this choice of score computation. As it was not the case, our data greatly evidence that inhibition with advancing age is not mainly explained by a slowdown in processing speed.

Moreover, many of these studies systematically used the Stroop task to assess inhibition. A recent study by Wolf et al. (2014) investigating the effect of age on inhibition and processing speed found that inhibition, as measured by the Stroop task, would decrease with age by itself and that this decrement cannot be explained by a general slowing. Furthermore, as previously discussed, inhibition seems itself to be a mediator variable and is postulated to play a very central role in cognition (e.g., Hasher & Zacks, 1988). So, we could postulate that inhibition plays a role as important as processing speed to explain changes in complex cognition including executive functioning associated with normal aging. For example, Van der Linden et al. (1999) using latent-construct structural equation modeling showed that significant relationships between age and language performance are mediated by reductions in speed, resistance to inference and working memory. Further studies will be obviously necessary to test these hypotheses.

FUTURE PERSPECTIVE

In future investigation, it would be interesting to analyze the relation between age, processing speed, attention, executive functions and the cognitive reserve built by older people throughout the lifespan. According to Stern (2002), the concept of cognitive reserve relates to brain network utilization efficiency in the sense of a more efficient synaptic processing or the use of alternative brain networks when required. In the aging context, the classical hypothesis is that people with a higher level of cognitive reserve would better resist to deleterious age effects and would have better cognitive performances as compared to aged people with a lower level of cognitive reserve. With regard to this latter point, Roldán-Tapia, García, Cánovas and León (2012) evidenced better performances on a Stroop task, the Trail Making Test and different WAIS subtests in aged people with a high cognitive reserve, as indexed by the educational level, the occupational attainment and the vocabulary level. A main factor of cognitive reserve in older people is the educational level (see Bennett et al., 2003; Meguro et al., 2001; Springer, McIntosh, Winocur, & Grady, 2005). Consequently, we consider that variability in cognitive reserve did not impact our results as we controlled for the

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educational level in the first step of all analyses. Interestingly, different factors of cognitive reserve would have an impact on specific executive processes (Hultsch, Hertzog, Small, & Dixon, 1999; James, Wilson, Barnes, & Bennett, 2011; Le Carret et al., 2003; Shimamura, Berry, Mangels, Rusting & Jurica, 1995). Therefore, future investigation should take those different cognitive reserve factors into account and to test the possible influence of each factor on our mediation analyses.

CONCLUSION

Results obtained here emphasize that processing speed is the most prominent mediator explaining age-related effects on executive functioning, even if this effect is partial and does not totally suppress the effect of age. It is in great agreement with Salthouse's work assuming a large influence of processing speed on various cognitive variables in normal aging (Salthouse, 1996). However, contrary to our expectations based on young participants, we did not observe a major influence of attentional variables on executive efficiency and some exploratory *post-hoc* analyses suggest that inhibition could be another important mediator. These results, particularly the relative contribution of processing speed and inhibition, have to be confirmed in further studies but suggest that the relationships between attention, processing speed and executive functioning could be modified with age.

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ENDNOTES

1 The alerting network comprises frontal and parietal areas and allows maintaining an alert state and a phasic reaction to a cued signal. The orienting network comprises the temporal parietal junction, the superior parietal lobe, and frontal eye field (Corbetta & Shulman, 2002) and allows selection of information. The executive control network comprises the anterior cingulate and lateral prefrontal cortex (Fan, Fossella, Sommer, Wu, & Posner, 2003; Fossella et al., 2002) and is responsible for cognitive and emotional auto-regulation.

2 Moreover, participants were also excluded from the study a) if we did not possess at least three executive composite scores (see below for details on composite score computation) in older participants and at least four executive composite scores in young participants. This criterion was a little less severe for older participants because the sample was smaller; b) if we did not have at least four measures assessing the attentional system; c) if we did not possess at least three measures assessing processing speed. Finally, if a participant did not have at least two different measures for a particular function, we decided not to compute the composite score on the function for this participant, what gave rise to four missing values.

3 Some studies have evidenced a certain influence of processing speed on inhibitory tasks in normal aging (de Ribaupierre, 1995; Hogge et al., 2008; Salthouse, 1992; Salthouse & Meinz, 1995; Verhaegen & Cerella, 2002; Verhaeghen & De Meersman, 1998). This is the reason why many authors (de Frias et al., 2006; Delaloye et al., 2009; Ludwig et al., 2010) rightly prefer to adopt relative scores that control for individual differences – namely, baseline *processing speed* individual difference – in their analyses instead of simple difference score. However, the choice of score computation has to be done according to each study design. Given that we were interested in the mediation effect of processing speed between age and inhibition, we use simple difference score (MacLeod, 1991) to avoid to control for processing speed in our interference scores.

4 We have added the adjective « so-called » because we do not fully agree with this conceptualization tending to "merge" attention and executive concepts as being all attentional. Rather, we theoretically prefer to distinguish between attentional and executive functions.

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SUPPLEMENTAL DATA

Table 14. Repartition of Young and Older participants as a function of their highest obtained educative degree.

	Young	**Older**
Primary (6 years)	0	2
Secondary – Inferior (>6 - 9 years)	0	7
Secondary – Superior (>9 - 12 years)	48	41
Superior – Short type (>12 - 15 years)	40	8
Superior – Long type (>15 - 17+ years)	16	5

Note. This repartition is based on the Belgian educative system. Participants must have reached the maximum number of educative years of a range degree to be attributed with this rank.

Table 15. Internal reliability of the executive and processing speed tasks.

Task	Reliability	Nb. subjects	Reference
Plus-Minus	N.A.[a]	N = 137	Miyake et al. (2000)
Number-Letter	.91[b]	N = 137	Miyake et al. (2000)
Local-Global	.59[b]	N = 137	Miyake et al. (2000)
Semantic Keep Track	.31[c]	N = 137	Miyake et al. (2000)
Tone monitoring	.63[c]	N = 137	Miyake et al. (2000)
Letter memory	.42[c]	N = 137	Miyake et al. (2000)
Anti-saccade	.77[b]	N = 137	Miyake et al. (2000)
Stop-Signal	.92[b]	N = 137	Miyake et al. (2000)
Stroop	.72[b]	N = 137	Miyake et al. (2000)
PASAT	.90[c]	N = 152	Crawford, Obonsawin, & Allan (1998)
Brown-Peterson	N.A.[d]	-	-
Letter comparison	.94[b]	N = 233	Salthouse & Babcock, 1991
Articulatory speed	N.A.[d]	-	-
Grapho-Motor addition	.93[b]	N = 240	Adapted from Salthouse & Coon (1994)

Note.
[a] Reliability could not be calculated for this task because there was only one RT per condition.
[b] Reliability was calculated by using the split-half correlations adjusted by the Spearman-Brown formula.
[c] Reliability was calculated using Cronbach's alpha.
[d] No available data.