AGING, NEUROPSYCHOLOGY, AND COGNITION, 2017
VOL. 24, NO. 5, 575–599
https://doi.org/10.1080/13825585.2016.1237613

Saccadic eye movements: what do they tell us about aging cognition?

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ABSTRACT

Although the relationship between age-related cognitive decline and saccadic eye movement (SEM) deficits has been outlined, specific cognitive alterations underlying age-related changes in saccadic performance remain unclear. This study attempted to better understand the nature of aging effects on SEMs. We compared SEMs in younger and older adults in prosaccade (PS) and antisaccade (AS) tasks under gap, step, and overlap conditions. We also examined relationships between these performances and several neuropsychological scores. Twenty-eight younger adults (YA), 24 older adults under 65 years ($OA_{<65}$) and 24 over 65 years ($OA_{>65}$) of age completed a neuropsychological evaluation, PS and AS tasks. Our results showed that latencies, AS cost, time to correct AS errors, and uncorrected AS, increased with aging. YA showed higher overlap effects than $OA_{>65}$ and $OA_{<65}$. Importantly, correlations and regressions revealed close relationships not only between latencies and processing speed measures but also between the AS cost and the inhibition process measures. Correct saccades and the time to correct AS errors were closely related to the inhibition process and cognitive flexibility measures. These findings suggest that the progressive age-related decline of processing speed and executive attention are associated with, and can be highlighted though SEMs in PS and AS tasks.

ARTICLE HISTORY
Received 21 April 2016
Accepted 10 September 2016

KEYWORDS
Eye tracking; elderly; processing speed; attention; working memory

Introduction

Ocular saccades, that are little ordinary rapid eye movements – made more than 100,000 times per day – play an increasingly more important role in different research domains such as neuroscience, psychiatry, or psychology. Eye movement paradigms are very useful in multiple research domains because their measures are relatively easy to obtain and the experimental tasks tend to be short, simple, and easily understood by participants (e.g., children, adults but also patients suffering from dementia). They are also adaptable to be used for several purposes (Klein & Ettinger, 2008). Moreover, eye

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tracking can be carried out in many healthy and clinical populations (i.e., speech, hearing, or body movements are not required).

These advantages allowed researchers to develop a rich body of empirical knowledge, however, there are gray areas that still remain in the understanding of the relationship between saccadic eye movements (SEM) and cognition. Literature on eye movements has demonstrated abnormal SEM in several psychiatric and neurological pathologies (Anderson & MacAskill, 2013; Carvalho et al., 2015; Leigh & Zee, 2005). However, the characterization of pathological behaviors requires an accurate knowledge of what constitutes normal behaviors in the healthy population. In the present study, we examined the impact of normal aging on SEM parameters. We also investigated the involvement of cognitive processes thought to play a role in the execution of SEMs in two well-known paradigms, the pro and antisaccade (AS) paradigms (Hutton, 2008). Based on several studies documented below, we assumed that the decline of specific cognitive functions associated with aging (Glisky, 2007; Salthouse, 2004) could be embodied in specific SEM-related behaviors.

In the prosaccade (PS) paradigm, participants are typically instructed to first fix their gaze on a central dot. Then, they have to stare as quickly as possible at a target dot appearing at the periphery of the central dot. AS tasks are more complex than PS tasks. Like in PS tasks, participants are instructed to first fix their gaze on a central dot until a target dot appears at the periphery of the central dot. In AS tasks, participants have to direct their gaze in the opposite direction to the target dot location. This SEM requires to inhibit the visually guided exogenous triggering toward the target, and to trigger a saccade in the opposite direction to the target (Munoz & Everling, 2004).

It has been demonstrated that, although saccade latency should theoretically be lower than 100 ms, typical saccade latency is approximately 200 ms, with a large variability (Carpenter, 1981). This longer delay is attributed to a “decision time” needed to accumulate and process information in order to decide when to trigger a saccade. The process underlying saccade triggering is time consuming and the delay in triggering saccade depends upon basic information processing efficiency and the cognitive process involved in the task such as attentional control or working memory (Hutton, 2008). This explains why there is normally a wide distribution of saccade latencies and also why AS generation implies a supplementary delay than in PS in both younger and older adult populations: inhibit saccade triggering toward the target, and to trigger saccade in the opposite direction to the target (Evdokimidis et al., 2002; Everling & Fischer, 1998; Munoz, Broughton, Goldring, & Armstrong, 1998; Munoz & Everling, 2004; Tatler & Hutton, 2007).

Despite a larger latency variability in older adults (Abel, Troost, & Dell’Osso, 1983; Klein, Fischer, Hartnegg, Heiss, & Roth, 2000; Peltsch, Hemraj, Garcia, & Munoz, 2011), studies on aging and SEM have demonstrated that we can distinguish younger from older adults’ latency distributions. Indeed, studies have commonly found greater latency in both PS and AS in comparison with younger adults (Abel & Douglas, 2007; Abel et al., 1983; Bono et al., 1996; Butler, Zacks, & Henderson, 1999; Crawford et al., 2013; Huaman & Sharpe, 1993; Kapoula et al., 2010; Klein et al., 2000; Litvinova et al., 2011; Moschner & Baloh, 1994; Munoz et al., 1998; Olincy, Ross, Youngd, & Freedman, 1997; Peltsch et al., 2011; Schik, Mohr, & Hofferberth, 2000; Sweeney, Rosano, Berman, & Luna, 2001; Yang &

Kapoula, 2006; Yang et al., 2006). Authors generally assume that the overall increase in saccade latency associated with aging is related to a decline of information processing speed (i.e., the reduction in the speed of the trigger and execution of cognitive operations). Neuronal degeneration or hypofunction of some cortical areas involved in the programming of SEM could be behind the latency increase (Kapoula et al., 2010; Yang & Kapoula, 2006). Research demonstrating an age-related anterior–posterior cortical decline (Dennis & Cabeza, 2008) is coherent with alterations of cortical areas such as the frontal eye field (FEF) and the dorsolateral prefrontal cortex (DLPFC), particularly involved in the initiation, the control, and the decisional process of saccades (Domagalik, Beldzik, Fafrowicz, Oginska, & Marek, 2012; Matsuda et al., 2004; McDowell, Dyckman, Austin, & Clementz, 2008; ; Munoz & Everling, 2004; Pierrot-Deseilligny, Milea, & Müri, 2004; Pierrot-Deseilligny, Müri, Ploner, Gaymard, & Rivaud-Péchoux, 2003).

In addition to the decline of information processing speed, the age-related modifications of latency can also reflect other specific cognitive processes. In interesting variants of the PS task, the central dot disappears before the onset of the target dot (namely the "Gap" condition) or the central dot remains visible after the onset of the target dot (namely the "Overlap" condition). PS latency – as well as AS latency – are generally reduced in the gap condition whereas they are increased in the overlap condition (Crevits & Vandierendonck, 2005; Fischer & Weber, 1993; Kristjánsson, Vandenbroucke, & Driver, 2004; Reuter-Lorenz, Hughes, & Fendrich, 1991; Saslow, 1967). It has been argued that the gap effect (i.e., the latency difference between gap and overlap conditions) is due to the early inhibition of the fixation cells and disinhibition of movement cells in the superior colliculus (SC) allowing saccade generation. This inhibition–disinhibition mechanism is modulated by attentional selection of stimuli (Clark, 1999; Pratt, Lajonchere, & Abrams, 2006). In the gap condition, just before the target appears, there is no stimulus on the screen. Therefore, selective attention is not required and the target can capture attention faster than in the overlap condition, where selective attention is focused on the central dot when the target appears.

Although poorly studied in comparison with standard measures associated to PS and AS tasks, the gap effect has been found to be similar in younger and older adults (Eenshuistra, Ridderinkhof, & Van Der Molen, 2004; Munoz et al., 1998; Peltsch et al., 2011; Yang & Kapoula, 2006; Yang et al., 2006). At first sight, these findings may be interpreted as reflecting a selective attention preservation in older adults. However, this conclusion is puzzling because it is known that older adults have difficulty in suppressing attentional capture (Zanto & Gazzaley, 2014). We should rather anticipate that no difference in the gap condition emerges between younger and older adults, but that older adults have a lower saccade latency than younger adults in the overlap condition. We hypothesized that the gap–overlap effect calculation has not been appropriate in most of the reviewed studies. The absence of a baseline such as step condition (i.e., the offset of the central dot coincides with the onset of the target dot) does not allow researchers to distinguish the gap effect from the overlap effect. For instance, it is possible that despite a similar gap–overlap contrast between younger and older adults, the age-related difference for the gap–step contrast be lower than that for the overlap–step contrast. Using the step condition as a baseline performance, and calculating a gap–step ratio and an overlap–step ratio should be a good alternative to examine the impact of age on gap and overlap effects.

Although latency is a parameter of high relevance to the study of SEM-cognition relationships, other parameters, especially in the AS task, can also reflect other aspects of cognitive processing. The increase in AS latency and the higher error rate found in older adults have been interpreted as a normal age-related decline of inhibitory function (Klein et al., 2000; Peltsch et al., 2011; Sweeney et al., 2001). In the AS, the attentional capture triggered by the peripheral target appearance leads to a competition race between parallel PS and AS activations (Godijn & Kramer, 2008; Kristjánsson, 2007; Massen, 2004). If attentional control is effective, the AS is then programmed fast enough, enabling the inhibition of the PS and the triggering of correct AS. Working memory capacity could also account for the differences between younger and older adults in the AS task (Crawford et al., 2013; Eenshuistra et al., 2004). For instance, by varying memory-updating requirements during AS tasks, Eenshuistra et al. (2004) have shown that, when working memory capacity is taxed, AS cost (i.e., the difference between AS and PS latency) increased in both younger and older adults but AS errors increased only in older adults. Comparing AS task performances with neuropsychological tests assessing inhibition and working memory processes, Bowling, Hindman, and Donnelly (2012) found that the latency and the percentage of uncorrected AS errors correlated with both spatial working memory and inhibition tests. However, the role of working memory in AS generation also remains debatable because some studies failed to find a direct relationship between working memory and AS performances (Crawford, Parker, Solis-Trapala, & Mayes, 2011; Hutton et al., 2004). The term “working memory” is often used in a rather vague sense – sometimes confounded with short-term memory, sometimes related to executive processes, or even not defined at all – which makes any direct comparison between results in this domain difficult. Moreover, the tests used to evaluate working memory are various. This does not allow to determine the specific processes that are involved, and potentially contributes to the heterogeneity of the findings.

Overall, controlled attention (i.e., the different processes that control and orient attention toward relevant information) seems to play a key role in AS task performance. Rather than separate inhibition and working memory process, we proposed to collect them by using the executive attention component from controlled attention model of working memory such as the one proposed by Engle, Kane, and Tuholski (1999). The executive attention allows maintaining task goals and managing the potential conflict between two competitive responses when usual responses can compete with unusual responses relevant for the goals of the current task (Engle & Kane, 2004). Therefore, goal maintenance, inhibition, and cognitive flexibility abilities (i.e., the ability to switch from one behavior to another behavior as a function of their relevance for the task) may refer as three components of executive attention in working memory (Miyake et al., 2000). Although close to the central executive component of the Baddeley’s working memory model (Baddeley, 2007), the executive attention component described by Engle and Kane (2004) permits a more functional approach and emphasizes the interaction between attentional, executive and mnesic processes within the working memory system.

In the context of SEMs, executive attention could specifically explain the performances in AS tasks as well as the difference between younger and older adults. AS control requires a higher executive attention involvement than the PS control leading to higher AS cost. We hypothesized that AS errors are due to a momentary drop in executive attention efficacy which prevents saccade triggering inhibition. When an AS error occurs, the triggering of PS could play the role of a reactivation signal which would enable the participant to correct the nonrelevant behavior and to redirect the saccade away from the target. Based on previous research showing executive attention alteration in aging (Braver & West, 2008), we suggested that inhibiting PS triggering in AS task requires supplementary delay in older adults. Older adults should also make more uncorrected AS errors and, at least, spend more time to correct their errors than younger adults.

The aim of the present experiment was to test the assumptions that, in addition to a decline of processing speed, SEMs can reflect a decline of controlled attention capacities in aging. Younger and older participants performed PS and AS tasks under gap, step, and overlap conditions. They also completed a neuropsychological assessment that included a free and cued recall test (FCRT) for episodic memory, forward (FDS) and backward digit spans (BDS) for short-term and working memory, the Trail Making Test (TMT) A and B for processing speed, and cognitive flexibility and the Stroop test for controlled attentional processing.

A final important point that we took into account was the age criterion usually chosen to constitute older adult groups. As regards eye movement domain, although there is consensus regarding the impact of age on latency, some studies failed to find error rate differences between older and younger adults (Bowling et al., 2012; Eenshuistra et al., 2004; Pratt, Dodd, & Welsh, 2006). One explanation could be the relatively “low” mean age of the elderly populations (M = 66 years) used in the latter studies. The mean age of the elderly populations used in the other studies was situated between 70 and 80 years of age. It is possible that the decline of cortical processing speed begins early whereas the controlled attention process is impacted later. This assumption may be related to research showing age-related alterations follow linear or quadratic decline as a function of the cognitive process involved (Borella, Carretti, & De Beni, 2008). This hypothesis could link studies which did not find age effect on AS errors rates – for older participants with a mean age of 66 – with those who did find age effects on both latency and AS errors rates – for older adults with a mean age between 70 and 80. This idea is also coherent with studies showing that latency gradually increases after 40 years until, at least, 80 years (Litvinova et al., 2011; Munoz et al., 1998). In order to verify that all SEM parameters are not influenced by aging in the same manner at the same time, we chose to examine the SEM differences between younger adults (YA) and two older adult groups: one under and one over 65 years ($OA_{<65}$ and $OA_{>65}$).

Based on previous studies cited above which suggested that the higher PS and AS latencies in older adults were related to the general early age-related decline in speed processing, we expected that $OA_{>65}$ would have higher latency than YA and $OA_{<65}$, and $OA_{<65}$ would have higher latency than YA, in all SEM latency measures. The alteration of executive attention in older adults should underline more difficulties to cope with the cognitive demand requiring to inhibit saccade toward the target and to trigger correct AS. Moreover, we suggested that the controlled attention process declines later in aging. This would result in higher AS cost and lower proportion of correct AS for $OA_{>65}$ than for YA and $OA_{<65}$. The ability to correct AS errors depending on executive attention, especially cognitive flexibility, $OA_{>65}$ should have a higher proportion of uncorrected

AS. They would also spend more time to correct AS errors when they succeed in correcting them, in comparison with YA and $OA_{<65}$. Similarly, given that selective attention is mainly involved in the overlap effects and that the former is altered in aging, we expected that gap–step ratio should not differ between our three groups whereas $OA_{>65}$ should have a lower overlap–step ratio than YA and $OA_{<65}$. Overall, neuropsychological tests assessing processing speed should correlate with, and be good predictors of, PS and AS latency. Neuropsychological tests assessing controlled attention should correlate with, and be good predictors of, AS cost and a proportion of correct AS. Those assessing more specifically cognitive flexibility should correlate with, and be good predictors of, the proportion of corrected and uncorrected AS errors, and with the time to correct AS errors.

Methods

Participants

Ninety participants were included in the experiment. Participants were divided into three groups: younger adults (YA), older adults under 65 years of age ($OA_{<65}$), and older adults over 65 years of age ($OA_{>65}$). Younger participants were students in the department of psychology from the University of Franche-Comté. Older adults were recruited by an advertisement in the Open University of Franche-Comté and in “Senior’s house” (a welcome and information center for older persons) in Besançon. Exclusion criteria stated that participants did not have neurological, psychiatric, or visual disorders, and they had never taken psychotropic drugs. Three YA, 6 $OA_{<65}$, and 6 $OA_{>65}$ participants were excluded because of problems with eye tracking calibration or recording, psychotropic drug uptake, or failure to complete the neuropsychological test battery. Thus, statistical analyses were computed on 28 YA (13 women, age range: 19–25, $M = 20$, $SD = 1.79$), 24 $OA_{<65}$ (10 women, age range: 55–64, $M = 59$, $SD = 3.18$), and 24 $OA_{>65}$ (11 women, age range: 66–85, $M = 75$, $SD = 5.88$). Number of years of education completed differed between the three groups ($H[2, N = 76] = 15.65$, $p < .001$): $OA_{<65}$ ($M = 10.5$; $SD = 3.20$) had less years of education than YA ($M = 12.5$; $SD = 1.48$, $p = .02$, $d = 0.82$), and $OA_{>65}$ ($M = 13.3$; $SD = 2.90$, $p < .001$, $d = 0.92$), whereas there was no statistical difference between YA and $OA_{>65}$ ($p = .51$, $d = 0.35$). Included participants reported good state of health, no visual, neurological, or psychiatric disorders and they had a normal or corrected-to-normal vision. Prior to the PS and AS task recording and after the eye tracker calibration, participants performed two preliminary tasks in order to check their ability to detect all the peripheral targets on the screen. All participants gave their written informed consent prior to inclusion into the study.

Material and procedure

Preliminary visual check-up

In the first preliminary task, a series of 16 target dots appeared at ±3°, ±6°, ±9°, and ±12° of visual angle from a central dot in the horizontal and vertical plane. Participants were instructed that they had to keep their gaze fixed on the central dot and to press on the keyboard when they detected the target. In the second preliminary task, 16 horizontal or vertical series of 1, 2, 3, or 4 dots were randomly presented on the screen and the participants had to say orally how many dots were displayed while they had to keep their gaze fixed on a central dot. These tasks allowed us to verify that participants were able to detect peripheral targets while their gaze was kept on the central dot (checked by eye tracking records). All of the participants performed the tasks without any errors.

Neuropsychological assessment

All participants completed a detailed battery of neuropsychological assessments. The battery included the following tests (all means and statistical analyses are shown in Table 1).

The Mini Mental State Evaluation (MMSE: Folstein, Folstein, & McHugh, 1975) provided us with a measure of general cognitive efficiency. Participants' scores on the MMSE were within the norms for the respective ages and numbers of education years completed (Crum, Anthony, Bassett, & Folstein, 1993; Ferreira et al., 2010).

The FCRT (Grober, Buschke, Crystal, Bang, & Dresner, 1988; Van der Linden et al., 2004) provided a measure of *episodic memory*. The participant has to learn a list of 16 words. The test includes an immediate recall phase (IR), three free recall phases (FR) and three cueing recall phases (CR). The IR provides a measure of memory encoding, the addition of the three FR provides a measure of memory recuperation and the addition of the three FR and CR (i.e., total recall, TR) provides a measure of memory storage.

The FDS and BDS tasks from the Wechsler Adult Intelligent Scale IV (WAIS IV: Wechsler & Naglieri, 2008) were used as *short-term memory and working memory* measures, respectively. The experimenter reads a sequence of numbers. The participant then has to recall the numbers in the same order for the FDS, and then in a reversed order for the BDS. The number sequences start with two numbers, following by three numbers, four numbers (etc.) until the participant fails to reproduce the sequence.

We also used the TMT A and B (Reitan, 1958). In part A, the participant has to connect, as quickly as possible and in the numerical order, the encircled numbers (from 1 to 25) randomly distributed on a white sheet. In part B, the participant has to alternatively

Table 1. Mean (standard deviation) and statistical tests for neuropsychological data.

Neuropsychological tests	YA	OA$_{<65}$	OA$_{>65}$	*F*	*K*	*p*
MMSE	28.54 (1.20)	27.95 (1.43)	28.09 (1.60)	1.2		=.31
TMTA^{a,b,c}	20.68 (5.17)	28.45 (8.35)	44.33 (21.53)		35.27	<.001
TMTB^{a,b}	64.18 (20.94)	88.86 (38.03)	138.76 (100.07)		19.28	<.001
FCSRT IR	15.86 (0.45)	15.77 (0.68)	15.58 (0.78)		3.25	=.20
FCSRT FR^{a,b}	36.57 (4.99)	33.00 (5.01)	29.92 (6.95)	8.85		<.001
FCSRT TR	46.86 (0.97)	46.59 (1.98)	46.17 (2.39)		0.52	=.77
FDS	6.21 (1.07)	6.05 (1.17)	6.00 (0.82)		0.34	=.84
BDS	4.82 (1.25)	4.32 (1.09)	4.09 (0.92)	2.88		=.06
Stroop W: Time (s)^{b,c}	58.21 (9.80)	56.59 (14.93)	75.15 (14.10)	13.59		<.001
Stroop C: Time (s)^{b,c}	41.21 (7.49)	41.77 (6.09)	50.38 (9.21)		10.06	<.001
Stroop CW Index: Time (s)^{a,b}	42.64 (27.75)	52.82 (14.23)	85.24 (69.74)	6.33		=.003

YA: younger adults; OA$_{<65}$: older adults under 65 years; OA$_{>65}$: older adults over 65 years; MMSE: Mini Mental State Evaluation; TMTA, B: Trail Making Test part A, part B; FCSRT IR, FR, TR: Free and Cued Recall Test, Immediate recall, Free Recall, Total recall; FDS: Forward Digit Span; BDS: Backward Digit Span; Stroop W, C, CW: Stroop test Word board, Color board, Color/Word board. Values for the ANOVA *F*-tests are indicated in the *F* column. If the data did not comply with the ANOVA parameters (heterogeneity and normality), we used Kruskal–Wallis *K*-tests as a nonparametric statistical test (*K* column). Exponents represent significant differences between (a) YA and OA$_{<65}$; (b) YA and OA$_{>65}$; (c) OA$_{<65}$ and OA$_{>65}$.

connect encircled numbers (from 1 to 13) and encircled letters (from A to L) in numerical and alphabetical orders as quickly as possible. It has been acknowledged that time to perform TMTA provides a measure of *processing speed* and time to perform TMTB provides a measure of *cognitive flexibility* (Bowie & Harvey, 2006).

Finally, we used the Stroop test (Meulemans, 2008; Stroop, 1935), which included three boards: a color board (C board), a word board (W board), and a color/word board (CW board). The participant has to successively read the color of the C board, then read the words of the W board, then ignore the words and read only the color of the words of the CW board. Each reading is timed and the errors are recorded. Times to perform W and C boards provide a measure of *processing speed* whereas the time index of the CW (i.e., $CW - C = CW_i$) provides measures of *controlled attentional processing* (i.e., *attentional inhibition ability*).

Eye movement paradigms

PS task. Each trial started with a central black fixation-point (0.5° of visual angle) on a gray background (RGB: 128, 128, 128). After 2000 ms, a yellow target-point (0.5° of visual angle) appeared for 2000 ms. The fixation-point was removed either 200 ms before (i.e., gap condition) or simultaneously (i.e., step condition), or 200 ms after (i.e., overlap condition) the onset of the target-point. The latter was displayed with an eccentricity of ±3°, ±6°, ±9° or ±12° of visual angle in the horizontal or the vertical plane. The target-point offset was followed by an inter-trial of 2000 ms. Then a new central fixation-point appeared to signal the start of the next trial. Participants were instructed to keep their gaze on the central fixation-point until the peripheral target-point appeared. At this time, they had to look at the target-point as accurately and quickly as possible.

AS task. The task was similar to the PS task except for the instructions given to the participants. Participants were similarly instructed to keep their gaze on the central fixation-point until the peripheral target-point appeared. However, after the onset of the target-point, they had to direct their gaze in the opposite direction to the target-point as quickly and accurately as possible.

Apparatus and eye movement recording

The participant was seated 60 cm in front of a remote video eye tracking system (ASL EYE-TRACK®6; Applied Science Laboratories; Bedford, MA) with a sampling rate of 60 Hz, a spatial resolution of 0.25° of visual angle, and a gaze position accuracy of 0.5° of visual angle. When the participant's right eye was correctly detected by the eye tracking system, a 9-point calibration was started. Once the calibration was successfully completed, the tasks began.

Stimuli were presented using *Inquisit 3.0.6.0* computer software (Millisecond Software; Seattle, WA), on an *Intel Pentium Dual Core 2.50 GHz* desktop computer. They were projected on a 19-inch monitor, with a resolution of 1280 × 1024 pixels and a screen refresh rate of 60 Hz.

Procedure

The experiment was divided into two sessions for each participant. In one session, participants took the neuropsychological assessment and socio-demographic interview for about 60 min. In the other session, participants performed the eye movement tasks for about 75 min. The order of the two sessions was counterbalanced across participants with a break of about 30 min between sessions to avoid fatigue.

Each participant performed four blocks of 96 trials which were counterbalanced as follows: PS–AS–PS–AS or AS–PS–AS–PS, with a 10-minute break between each block. Before each block, a new calibration was started and instructions were given to participants, both via the computer monitor and verbally by the experimenter. Then, four practice trials were performed to ensure that participants understood the upcoming task.

Data analysis

Saccade onset and offset were defined by a fixed velocity threshold of 30°/s (Crawford et al., 2013; Munoz et al., 1998; Peltsch et al., 2011; Sweeney et al., 2001). The direction of a saccade was identified by the eye position difference between the start and the end of the saccade. Trials where the saccade occurred more than 80 ms before (anticipatory saccade), or more than 800 ms after, the target onset (delayed saccade) were excluded from the analysis. Trials were also excluded when the eye tracker failed to record the eye coordinates (e.g., eye blink, loss of pupil or corneal reflection). *Correct saccades* were defined as saccades directed toward the target in PS and in the opposite direction in AS. Saccades directed toward the target in AS were defined as *AS error*. If there was a subsequent saccade in the opposite direction, AS error was categorized as *corrected AS error*. If the saccade was not corrected, AS error was categorized as *uncorrected AS error*. We did not analyze PS errors because their number was too low for an informative statistical analysis.

On the basis of these categorizations, we derived the following saccade parameters based on our eye movement recordings: the latency of saccades in a PS task, the latency of correct saccades and AS errors, the proportion (i.e., percentage of the total number of saccades) of correct saccades, corrected and uncorrected AS errors, and the time to correct AS errors in AS task. The difference between correct AS latency and PS latency were calculated to obtain and analyze AS cost. We also computed gap–step ratios (i.e., [gap − step]/[gap + step]) and overlap–step ratios (i.e., [overlap − step]/[overlap + step]) for each SEM variable just cited above.

In the first step, these parameters were analyzed with mix plot analyses of variance (ANOVA). Age (YA, $OA_{<65}$, and $OA_{>65}$) was the between-subjects factor, and condition (gap, step, overlap) the within-subject factor. As the distributions of latencies are not normally distributed and/or the variances not homogeneous, we used a logarithmic transformation (i.e., $\log_{10}(x)$). According to the Shapiro–Wilk test, we obtained normalized distributions after the transformations. When the assumption of sphericity was violated, we used the Greenhouse–Geisser's correction. Contrast analyses were used for group comparisons. In the second step, we performed Pearson's *r* correlations between neuropsychological tests and SEM variables. We finally computed stepwise multiple regressions with neuropsychological tests as potential predictors of each of the SEM variables.

Preliminary statistical analyses did not show any session order effect (all $F < 1.56$, all $p > .05$) and no interaction between session order and age (all $F < 0.99$, all $p > .05$) for all SEM variables. There was no task order effect (all $F < 3.40$, all $p > .05$) or no interaction between task order and age (all $F < 3.21$, all $p > .05$). Similarly, the age effects did not depend on eccentricity (all $F < 2.2$, all $p > .05$) or direction (all $F < 2.23$, all $p > .05$). These results allowed us to collapse the data across sessions and task orders and across eccentricity and direction to obtain the statistical plan described above.

Results

PS Latency

The ANOVA revealed a main effect of age ($F[2, 73] = 18.2$, $p < .001$, $\eta^2 = 0.33$, $\beta - 1 = .99$), which was qualified by an age × condition interaction ($F[4, 146] = 5.2$, $p < .001$, $\eta^2 = 0.12$, $\beta - 1 = .96$). $\text{OA}_{(>65)}$ latency was higher than YA and $\text{OA}_{(<65)}$ latency in gap ($F[1, 73] = 31.12$, $p < .001$, $d = 1.57$), Step ($F[1, 73] = 32.36$, $p < .001$, $d = 1.54$) or overlap condition ($F[1, 73] = 19.02$, $p < .001$, $d = 1.26$). $\text{OA}_{(<65)}$ latency was higher than YA latency in gap ($F[1, 73] = 6.84$, $p = .01$, $d = 0.60$) and step ($F[1, 73] = 8.98$, $p = .004$, $d = 0.88$) condition, but not statistically different in overlap condition ($F[1, 73] = 1.42$, $p = .24$, $d = 0.27$) (Table 2, Figure 1).

As regards the gap–step and the overlap–step ratios, a main effect of age was found ($F[2, 73] = 5.54$, $p = .006$, $\eta^2 = 0.13$, $\beta - 1 = .84$), which was also qualified by

Table 2. Mean (standard deviation) of prosaccade (PS) and antisaccade (AS) latency (ms), AS cost (ms), AS error latency (ms), time to correct AS errors (ms), and gap– and overlap–step ratios for each of these variables as a function of groups and conditions.

	Younger adults	Older adults (<65)	Older adults (>65)
PS latency			
Gap	208.70 (30.69)	231.00 (27.05)	269.69 (50.25)
Step	218.28 (30.01)	245.98 (25.51)	288.68 (61.32)
Overlap	256.47 (35.62)	269.12 (32.17)	312.53 (62.68)
Gap–step ratio	−0.02 (0.04)	−0.03 (0.03)	−0.03 (0.04)
Overlap–step ratio	0.08 (0.03)	0.04 (0.03)	0.04 (0.04)
AS latency			
Gap	329.72 (46.02)	364.20 (54.54)	410.53 (54.98)
Step	346.50 (50.75)	389.33 (43.43)	427.83 (42.31)
Overlap	384.11 (59.93)	421.62 (57.46)	453.96 (62.12)
Gap–step ratio	−0.07 (0.04)	−0.07 (0.03)	−0.05 (0.05)
Overlap–step ratio	0.05 (0.04)	0.04 (0.05)	0.03 (0.05)
AS cost			
Gap	214.16 (37.01)	203.74 (31.98)	247.56 (61.89)
Step	212.27 (56.12)	203.53 (44.54)	236.20 (62.15)
Overlap	214.08 (42.91)	216.45 (31.31)	245.43 (54.11)
Gap–step ratio	−0.004 (0.07)	−0.01 (0.06)	0.02 (0.06)
Overlap–step ratio	−0.008 (0.06)	0.02 (0.06)	0.02 (0.07)
AS error latency			
Gap	196.53 (26.21)	228.12 (20.93)	249.03 (30.88)
Step	215.78 (22.50)	242.24 (21.47)	280.21 (36.14)
Overlap	230.60 (25.82)	250.01 (20.48)	283.60 (49.67)
Gap–step ratio	−0.05 (0.05)	−0.03 (0.04)	−0.06 (0.05)
Overlap–step ratio	0.03 (0.04)	0.01 (0.03)	−0.001 (0.04)
Time to correct AS errors			
Gap	214.16 (37.01)	203.74 (31.98)	247.56 (61.89)
Step	212.27 (56.12)	203.53 (44.54)	236.20 (62.15)
Overlap	214.08 (42.91)	216.45 (31.31)	245.43 (54.11)
Gap–step ratio	−0.004 (0.07)	−0.01 (0.06)	0.02 (0.06)
Overlap–step ratio	−0.008 (0.06)	0.02 (0.06)	0.02 (0.07)

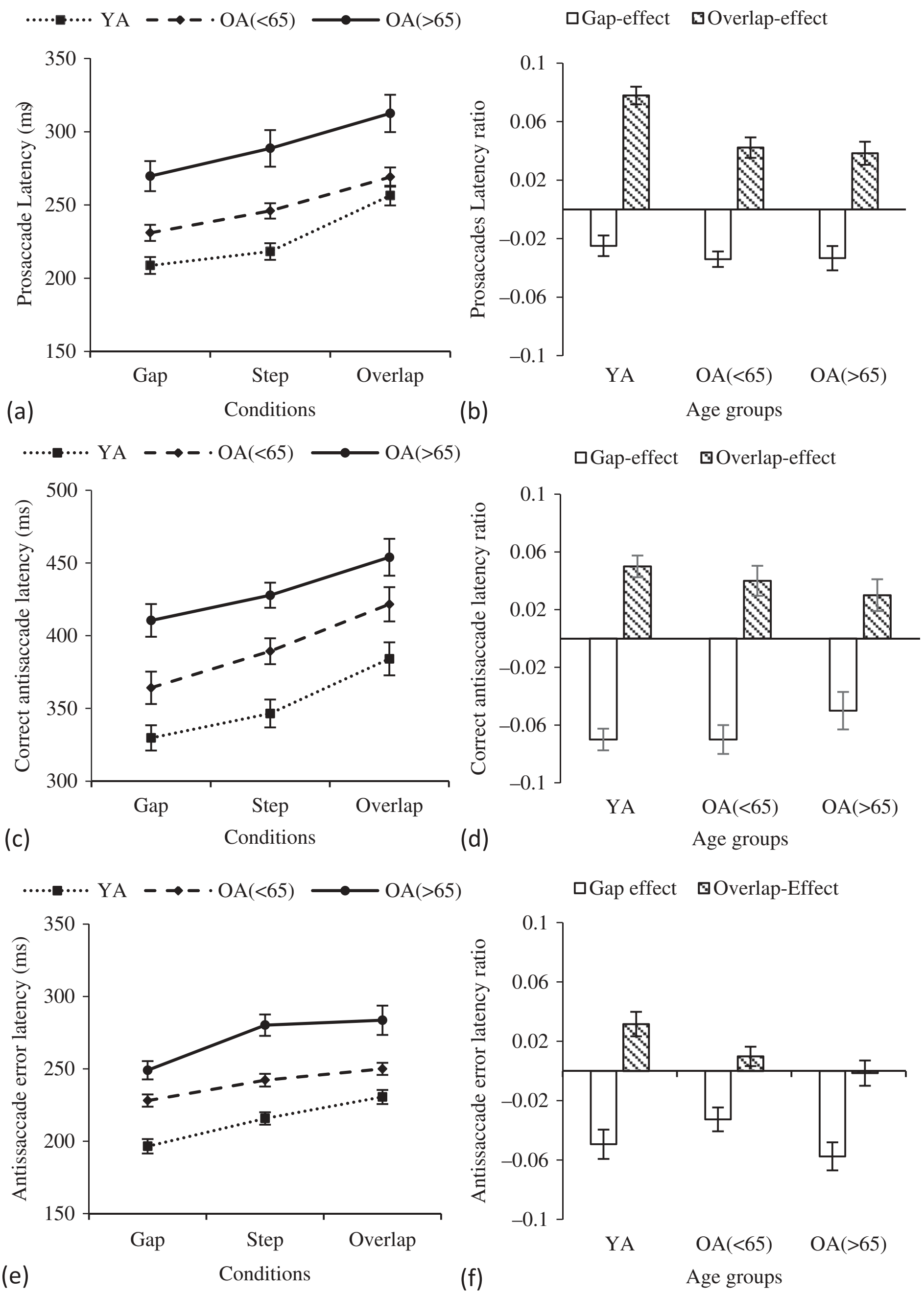

Figure 1. Left: Prosaccades (a), correct antisaccades (c) and corrected antisaccades (e) latency as a function of groups and conditions. Right: prosaccades (b), correct antisaccades (d) and corrected antisaccades (f) gap–step latency ratio (i.e., [gap – step]/[gap + step]) and overlap–step latency ratio (i.e., [overlap − step]/[overlap + step]) as a function of groups (Error bars: ±1 standard errors).

an age × condition interaction ($F[2, 73] = 4.94$, $p = .01$, $\eta^2 = 0.12$, $\beta - 1 = .79$). The gap–step ratio did not differ between the OA$_{(>65)}$ group and the YA and OA$_{(<65)}$ group ($F[1, 73] = 0.20$, $p = .66$, $d = 0.11$) or between the YA and OA$_{(<65)}$ group (F[1, 73] = 0.86, p = .36, d = 0.20). The overlap–step ratio was lower in the OA$_{(>65)}$ group than in the YA and OA$_{(<65)}$ group (F[1, 73] = 6.34, p = .01, d = 0.72). It was also lower in the OA$_{(<65)}$ group than in the YA group (F[1, 73] = 13.48, p < .001, d = 0.77).

Correct AS Latency

ANOVA revealed a main effect of age (F[2, 73] = 17.2, p < .001, η^2 = 0.32, β – 1 = .99) but the age × condition interaction was not statistically significant (F[4, 146] = 1.7, p = .16, η^2 = 0.04, β – 1 = 0.51). OA$_{(>65)}$ group (M = 430.77, SD = 47.47) had a higher latency than the YA and OA$_{(<65)}$ group (F[1, 73] = 23.80, p < .001, d = 2.92). OA$_{(<65)}$ group (M = 391.71, SD = 47.56) had higher latency than the YA group (M = 353.45, SD = 49.56, F[1, 73] = 9.26, p = .003, d = 1.10) (Table 2, Figure 1).

The gap–step and the overlap–step ratio analysis showed no main effect of age (F[2, 73] = 0.65, p = .52, η^2 = 0.02, β – 1 = .15) or age × condition interaction (F[2, 73] = 2.81, p = .07, η^2 = 0.32, β – 1 = .54).

AS error latency

A main effect of age (F[2, 73] = 35.3, p < .001, η^2 = 0.49, β – 1 = 1) was found. Age × condition interaction (F[3.63, 132.67] = 2.4, p = .06, η^2 = 0.06, β – 1 = .68) was not statistically significant. OA$_{(>65)}$ latency (M = 270.95, SD = 34.26) was higher than YA and OA$_{(<65)}$ latency (F[1, 73] = 47.65, p < .001, d = 1.99). OA$_{(<65)}$ latency (M = 240.13, SD = 17.76) was higher than YA latency (M = 214.61, SD = 21.61, F[1, 73] = 17.49, p < .001, d = 1.03) (Table 2, Figure 1).

As regards the gap–step and the overlap–step ratios, we did not find any main effect of age (F[2, 73] = 2.69, p = .07, η^2 = 0.07, β – 1 = .52), but age × condition interaction was statistically significant (F[2, 73] = 3.56, p = .03, η^2 = 0.09, β – 1 = .64). The overlap–step ratio was lower in the OA$_{(>65)}$ group than in the YA and OA$_{(<65)}$ group (F[1, 73] = 5.13, p = .03, d = 0.59). It was also lower in the OA$_{(<65)}$ than in the YA group (F[1, 73] = 3.91, p = .04, d = 0.28). The gap–step ratio effect did not differ between the OA$_{(>65)}$ group and the YA and OA$_{(<65)}$ groups (F[1, 73] = 2.06, p = .16, d = 0.41), and between OA$_{(<65)}$ and YA group (F[1, 73] = 1.66, p = .20, d = 0.19).

Time to correct AS errors

The ANOVA indicated only a main effect of age (F[2, 73] = 4.21, p = .02, η^2 = 0.10, β – 1 = .72). Age × condition interaction was not statistically significant (F[2, 146] = 0.83, p = .52, η^2 = 0.02, β – 1 = .26). Correcting AS errors took more time for OA$_{(>65)}$ (M = 242.80, SD = 55.70) than for YA and OA$_{(<65)}$ (F[1, 73] = 9.42, p = .003, d = 0.94). There was no difference between YA and OA$_{(<65)}$ (F[1, 73] = 0.15, p = .70, d = 0.07) (Table 2, Figure 2).

Concerning the gap–step and the overlap–step ratios, no main effect of age (F[2, 73] = 1.44, p = .24, η^2 = 0.04, β – 1 = .30) or age × condition interaction (F[2, 73] = 3.20, p = .05, η^2 = 0.08, β – 1 = .60) were statistically significant.

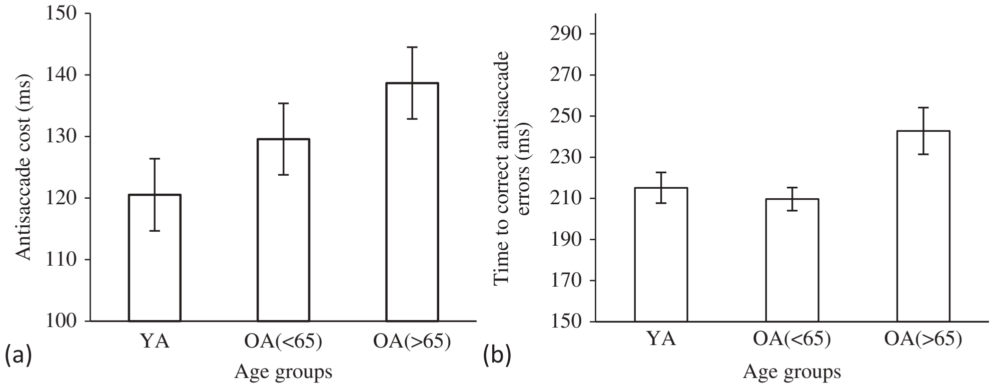

Figure 2. (a) Antisaccade cost (i.e., antisaccade latency − prosaccade latency) as a function of ages; (b) Time to correct antisaccade errors as a function of ages (Error bars: ±1 standard errors).

AS cost

A main effect of age was found ($F[2, 73] = 4.204$, $p = .02$, $\eta^2 = 0.11$, $\beta - 1 = .72$) but the age × condition interaction was not statistically significant ($F[4, 146] = 1.88$, $p = .13$, $\eta^2 = 0.05$, $\beta - 1 = .55$). The AS cost was higher in $\mathrm{OA}_{(>65)}$ ($M = 138.68$, $SD = 28.57$) than in YA and $\mathrm{OA}_{(<65)}$ ($F[1, 73] = 4.83$, $p = .03$, $d = 0.64$). There was no statistical difference between YA ($M = 120.53$, $SD = 41.63$) and $\mathrm{OA}_{(<65)}$ ($M = 131.57$, $SD = 28.44$, $F[1, 73] = 3.38$, $p = .07$, $d = 0.30$) (Table 2, Figure 2).

Concerning the gap–step and the overlap–step ratios, we found a main effect of age ($F[2, 73] = 4.87$, $p = .01$, $\eta^2 = 0.12$, $\beta - 1 = .79$) but no age × condition interaction ($F[2, 73] = 1.09$, $p = .34$, $\eta^2 = 0.03$, $\beta - 1 = .23$). Overall, ratios were higher in $\mathrm{OA}_{(>65)}$ group ($M = 0.07$, $SD = 0.24$) than in YA and $\mathrm{OA}_{(<65)}$ group ($F[1, 73] = p = .006$, $d = 0.78$). There was no difference between YA group ($M = -0.10$, $SD = 0.22$) and $\mathrm{OA}_{(<65)}$ group ($M = -0.03$, $SD = 0.10$, $F[1, 73] = 7.92$, $p = .006$, $d = 0.20$).

Proportion of correct ASs

Results indicated main effects of age ($F[2, 73] = 3.75$, $p = .03$, $\eta^2 = 0.09$, $\beta - 1 = 0.67$) but no age × condition interaction ($F[2, 146] = 1.55$, $p = .19$, $\eta^2 = 0.04$, $\beta - 1 = 0.47$). $\mathrm{OA}_{(>65)}$ ($M = 46.87$, $SD = 16.63$) had a lower percentage of correct AS than YA and $\mathrm{OA}_{(<65)}$ ($F[1, 73] = 6.66$, $p = .01$, $d = 0.74$). There was no difference between YA ($M = 58.46$, $SD = 23.45$) and $\mathrm{OA}_{(<65)}$ ($M = 62.56$, $SD = 18.10$, $F[1, 73] = 0.55$, $p = .46$, $d = 0.12$) (Table 3, Figure 3).

Concerning the gap–step and the overlap–step ratios, no main effect of age ($F[2, 73] = 1.67$, $p = .20$, $\eta^2 = 0.04$, $\beta - 1 = 0.34$) or age × condition interaction ($F[2, 73] = 1.43$, $p = .25$, $\eta^2 = 0.04$, $\beta - 1 = 0.30$) were statistically significant.

Proportion of corrected ASs

The ANOVA did not show any main effect of age ($F[2, 73] = 0.93$, $p = .40$, $\eta^2 = 0.02$, $\beta - 1 = .20$) or age × condition interaction ($F[3.66, 133.56] = 1.37$, $p = .25$, $\eta^2 = 0.04$, $\beta - 1 = .42$).

Table 3. Mean (standard deviation) of proportions of correct, corrected and uncorrected AS, and gap– and overlap–step ratios for each of these variables as a function of groups and conditions.

	Younger adults	Older adults (<65)	Older adults (>65)
Proportion of correct AS			
Gap	59.96 (25.27)	60.88 (20.11)	49.77 (18.51)
Step	52.43 (24.97)	58.28 (17.84)	43.41 (16.23)
Overlap	63.00 (22.60)	68.52 (19.76)	50.42 (18.34)
Gap–step ratio	0.09 (0.15)	0.01 (0.17)	0.07 (0.14)
Overlap–step ratio	0.13 (0.15)	0.09 (0.09)	0.06 (0.13)
Proportion of corrected AS			
Gap	38.43 (24.82)	34.56 (19.43)	39.18 (18.73)
Step	46.35 (24.21)	37.72 (17.15)	43.17 (17.36)
Overlap	35.44 (21.53)	28.21 (17.02)	37.08 (16.67)
Gap–step ratio	−0.12 (0.25)	−0.06 (0.19)	−0.06 (0.17)
Overlap–step ratio	−0.14 (0.15)	−0.15 (0.19)	−0.06 (0.15)
Proportion of uncorrected AS			
Gap	2.55 (4.15)	5.74 (8.19)	13.88 (11.36)
Step	2.20 (2.98)	5.82 (7.07)	15.29 (13.12)
Overlap	2.60 (4.95)	3.94 (6.68)	16.82 (13.75)
Gap–step ratio	−0.01 (0.23)	−0.03 (0.18)	−0.05 (0.19)
Overlap–step ratio	0.004 (0.20)	−0.09 (0.21)	0.08 (0.17)

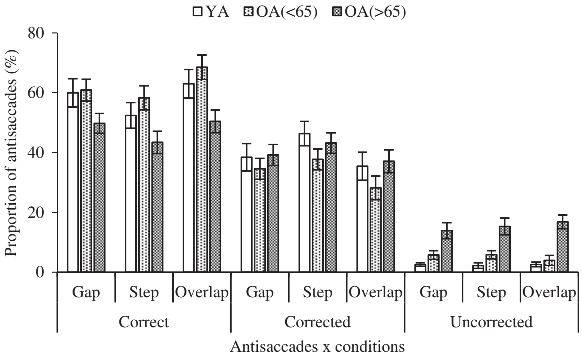

Figure 3. Proportion (i.e., percentage of the total number of saccades) of correct, corrected, and uncorrected antisaccades as a function of ages and conditions (Error bars: ±1 standard errors).

Concerning the gap–overlap effect, no main effect of age (F[2, 73] = 1.22, p = .30, η^2 = 0.03, β − *1* = .26) or age × condition interaction (F[2, 73] = 1.39, p = .25, η^2 = 0.04, β − *1* = .29) were statistically significant.

Proportion of uncorrected ASs

Results indicated a main effect of age (F[2, 73] = 16.48, $p < .001$, η^2 = 0.31, β − *1* = .99) but not age × condition interaction (F[4, 146] = 2.36, p = .051, η^2 = 0.06, β − *1* = .67). OA $_{(>65)}$ (M = 14.33, SD = 12.40) had a higher percentage of uncorrected AS than YA and OA $_{(<65)}$ (F[2, 73] = 16.48, $p < .001$, d = 1.64). There was no difference between YA (M = 2.45, SD = 3.68) and OA$_{(<65)}$ (M = 5.17, SD = 7.03, F[2, 73] = 16.48, $p < .001$, d = 0.25) (Table 3, Figure 3).

As regards the gap–step and the overlap–step ratios, although the main effect of group was not statistically significant ($F[2, 73] = 1.20$, $p = .31$, $\eta^2 = 0.03$, $\beta - 1 = .25$), a group × condition interaction ($F[2, 73] = 7.42$, $p < .001$, $\eta^2 = 0.17$, $\beta - 1 = .93$) was found (Table 3). The overlap–step ratio was lower in the $OA_{(>65)}$ group than in the YA and the $OA_{(<65)}$ groups ($F[1, 73] = 6.25$, $p = .01$, $d = 0.63$), but it was not statistically different between the YA and the $OA_{(<65)}$ group ($F[1, 73] = 2.87$, $p = .09$, $d = 0.37$). Concerning the gap–step ratio, the $OA_{(>65)}$ group did not differ from the YA and the $OA_{(<65)}$ group ($F[1, 73] = 0.32$, $p = .57$, $d = 0.18$) and the YA group did not differ from the $OA_{(<65)}$ group ($F[1, 73] = 0.15$, $p = .70$, $d = 0.06$).

Correlations and regressions

Correlations

Correlations between SEM and neuropsychological tests are presented in Table 4. Overall, measures of *processing speed* (TMTA, time of Stroop C and W) were positively correlated with all SEM latencies and the proportion of uncorrected AS, and negatively correlated with the proportion of correct AS. *Inhibition measures* (Stroop CW_i) were positively correlated with AS latency, AS cost (only in gap and step condition), time to correct AS errors and negatively correlated with the proportion of correct AS. *Cognitive flexibility* measures (TMTB) were positively correlated with SEM latencies, the time to correct AS errors, the proportion of uncorrected AS and negatively correlated with the proportion of correct AS. Interestingly, the free recall scores of the FCRT was positively correlated with the proportion of correct AS and negatively correlated with AS latency and the proportion of uncorrected AS. There were no additional correlations between neuropsychological measures and SEM parameters. No correlation was found between the number of years of education completed and SEM parameters or neuropsychological measures. Moreover, an ANCOVA was carried out on each SEM variables, in which the compared means were adjusted for the effect of education. These complementary analyses suggested that the level of education did not affect any effects previously reported in the ANOVAs: all differences remained statistically significant for each SEM variables, even when the number of years of education completed was added as covariant ($F_s > 4.5$, $p_s < .03$).

Multiple regressions

In order to examine the importance of the relationship between neuropsychological scores and SEM measures, we computed final stepwise multiple regressions with neuropsychological tests as predictors for each of SEMs variables. Table 5 indicates the significant neuropsychological score predictors for each of the SEM measures. Overall, *processing speed measures* (TMTA, time of Stroop C and W) were best predictors of all SEM latencies. *Inhibition measures* (Stroop CW_i) were the best predictors of AS cost (gap and step conditions), the proportion of correct AS (Gap and overlap conditions), and the proportion of corrected AS (gap and step conditions). *Cognitive flexibility* measure (TMTB) was best predictor of the time to correct AS errors and also a good predictor of the AS latency (overlap condition), the AS error latency (step condition), the proportion of corrected AS (Step and overlap condition), and the proportion of uncorrected AS.

Table 4. Correlations between saccadic eye movements and age, years of education completed and neuropsychological tests.

			TMT		Stroop			FCRT			Digit span			
		Age	A	B	C	W	CW$_i$	FR	TR	IR	Forward	Backward	MMSE	Years of education
Years of education		.028	.136	−.021	.149	.103	.147	.021	.077	−.066	.125	.229	.239	
Age			.576**	.486**	.351**	.338**	.391**	−.466**	−.179	−.198	−.085	−.284*	−.133	.028
PS latency	Gap	.531**	.267*	.301*	.333**	.382**	.176	−.197	−.115	−.101	−.076	−.179	.066	.179
	Step	.536**	.307**	.311**	.376**	.418**	.135	−.192	−.143	−.065	−.013	−.198	−.022	.233
	Overlap	.387**	.250*	.293*	.410**	.449**	.054	−.207	−.167	−.015	−.045	−.227	.051	.226
AS latency	Gap	.521**	.339**	.357**	.442**	.443**	.303*	−.319**	−.041	−.041	−.047	−.184	−.02	.020
	Step	.576**	.398**	.315**	.481**	.471**	.356**	−.336**	−.084	.011	−.041	−.122	−.125	.231
	Overlap	.413**	.332**	.404**	.386**	.434**	.273*	−.322**	−.095	−.112	−.079	−.171	−.035	.117
AS cost	Gap	.212	.197	.202	.214	.161	.252*	−.075	−.023	−.038	.067	−.124	−.112	.122
	Step	.202	.161	.062	.176	.141	.304*	−.192	−.020	.011	−.032	−.005	.046	.184
	Overlap	.162	.183	.140	.132	.147	.172	−.178	−.048	.041	.035	.007	−.044	.235
AS error latency	Gap	.639**	.325**	.324**	.121	.142	.157	−.194	−.052	−.177	.032	−.111	.065	.058
	Step	.663**	.418**	.463**	.392**	.405**	.241*	−.306**	−.200	−.167	.081	−.181	.014	.038
	Overlap	.487**	.245*	.259*	.310**	.343**	.091	−.230	−.127	−.095	.124	−.161	−.079	−.129
Time to correct AS errors	Gap	.110	.166	.412**	.311**	.284*	.281*	−.152	−.184	−.192	.030	−.008	.111	.176
	Step	.075	.117	.313**	.215	.218	.263*	−.059	−.125	−.198	.026	−.095	−.022	.046
	Overlap	.199	.153	.361**	.274*	.256*	.268*	−.167	−.182	−.208	−.037	.000	−.032	−.009
Proportion of correct AS	Gap	−.201	−.393**	−.353**	−.398**	−.323**	−.261*	.387**	.129	.084	.162	.128	−.114	−.054
	Step	−.151	−.430**	−.335**	−.353**	−.357**	−.253*	.290*	.044	.101	.238	.210	−.117	.007
	Overlap	−.219	−.445**	−.347**	−.362**	−.330**	−.262*	.313**	.061	.149	.225	.236	−.103	−.070
Proportion of corrected AS	Gap	.017	.218	.054	.209	.153	.217	−.194	.117	.017	−.160	−.073	.080	−.023
	Step	−.103	.205	−.013	.173	.201	.163	−.050	.205	−.007	−.223	−.130	.074	−.129
	Overlap	.002	.209	.055	.206	.203	.172	−.107	.121	−.058	−.217	−.166	.068	−.018
Proportion of uncorrected AS	Gap	.434**	.278*	.351**	.440**	.436**	.198	−.276*	−.163	−.144	.090	−.070	.089	.069
	Step	.482**	.297*	.445**	.494**	.437**	.277*	−.324**	−.212	−.142	.060	−.134	.090	−.022
	Overlap	.450**	.302*	.452**	.561**	.491**	.217	−.325**	−.205	−.219	.061	−.095	.059	.120

AS: Antisaccade; PS: Prosaccade; TMTA, B: Trail Making Test part A, part B; Stroop W, C, CW: Stroop test Word board, Color board, Color/Word board; FCSRT IR, FR, TR: Free and Cued Recall Test, Immediate recall, Free Recall, Total recall; MMSE: Mini Mental State Evaluation. *$p < .05$, ** $p < .01$.

Table 5. Multiple regression summary for significant predictors of SEMs.

Dependent variables		Predictors	F	Adj. R^2	β	sr^2
PS latency	Gap	Stroop W	11.09***	.13	.382**	.15
	Step	Stroop W	13.76***	.16	.418***	.18
	Overlap	Stroop W	16.40***	.19	.449***	.20
AS latency	Gap	Stroop W	15.86***	.18	.443***	.20
	Step	Stroop C	12.77***	.26	.414***	.18
		Stroop CWi			.241*	.07
	Overlap	Stroop W	10.74***	.23	.324**	.11
		TMT-B			.274*	.08
AS cost	Gap	Stroop CWi	4.41*	.05	.252*	.06
	Step	Stroop CWi	6.64*	.08	.304*	.09
	Overlap	–	0.6 *n.s.*	–	–	–
AS error latency	Gap	TMT-A	7.65**	.09	.325**	.11
	Step	TMT-B	11.97***	.25	.359**	.13
		Stroop W			.262*	.07
	Overlap	Stroop W	8.65**	.10	.343**	.12
Time to correct AS errors	Gap	TMT-B	13.33***	.16	.413***	.17
	Step	TMT-B	7.07**	.08	.313**	.10
	Overlap	TMT-B	9.75**	.12	.361**	.13
Proportion of correct AS	Gap	Stroop CWi	2.79**	.21	.369*	.10
	Step	Stroop C	2.49*	.18	.370*	.10
	Overlap	TMT-A	2.65**	.20	−.361*	.07
		Stroop CWi			.337*	.08
Proportion of corrected AS	Gap	Stroop CWi	5.41*	.06	.277*	.07
	Step	TMT-B	2.14*	.12	−.585*	.12
		Stroop CWi			.445*	.06
	Overlap	TMT-A	2.33*	.17	.452*	.11
		TMT-B			−.521*	.10
Proportion of uncorrected AS	Gap	TMT-A	2.97**	.23	−.348*	.07
		TMT-B			.470*	.09
	Step	TMT-B	3.82***	.30	.492**	.11
		Stroop C			.400*	.08
	Overlap	TMT-B	4.75***	.36	.564**	.15
		Stroop C			.471**	.12

AS: Antisaccade; PS: Prosaccade; TMTA, B: Trail Making Test part A, part B; Stroop W, C, CW: Stroop test Word board, Color board, Color/Word board. $^*p < .05$, $^{**}p < .01$, $^{***}p < .001$, *n.s*: non-significant.

There were no additional neuropsychological measures retained as predictors of SEMs in the multiple regression models.

Discussion

In the present study, we compared SEM in younger and older adults while they performed PS and AS tasks under different conditions (i.e., gap, step, and overlap). We also examined the relationships between SEM performances and scores obtained on several neuropsychological tests designed to measure specific cognitive processes such as processing speed, short-term and working memory, cognitive flexibility, and inhibition process, which were hypothesized to underlie SEM control (Figure 4).

As expected, and in agreement with the previously reported literature on eye movements, our findings showed that aging led to an increase in both PS and AS latency, AS cost, and uncorrected saccades (Abel & Douglas, 2007; Abel et al., 1983; Bono et al., 1996; Butler et al., 1999; Crawford et al., 2013; Huaman & Sharpe, 1993; Kapoula et al., 2010; Klein et al., 2000; Litvinova et al., 2011; Moschner & Baloh, 1994; Munoz et al., 1998; Olincy et al., 1997; Peltsch et al., 2011; Schik et al., 2000; Sweeney et al., 2001; Yang &

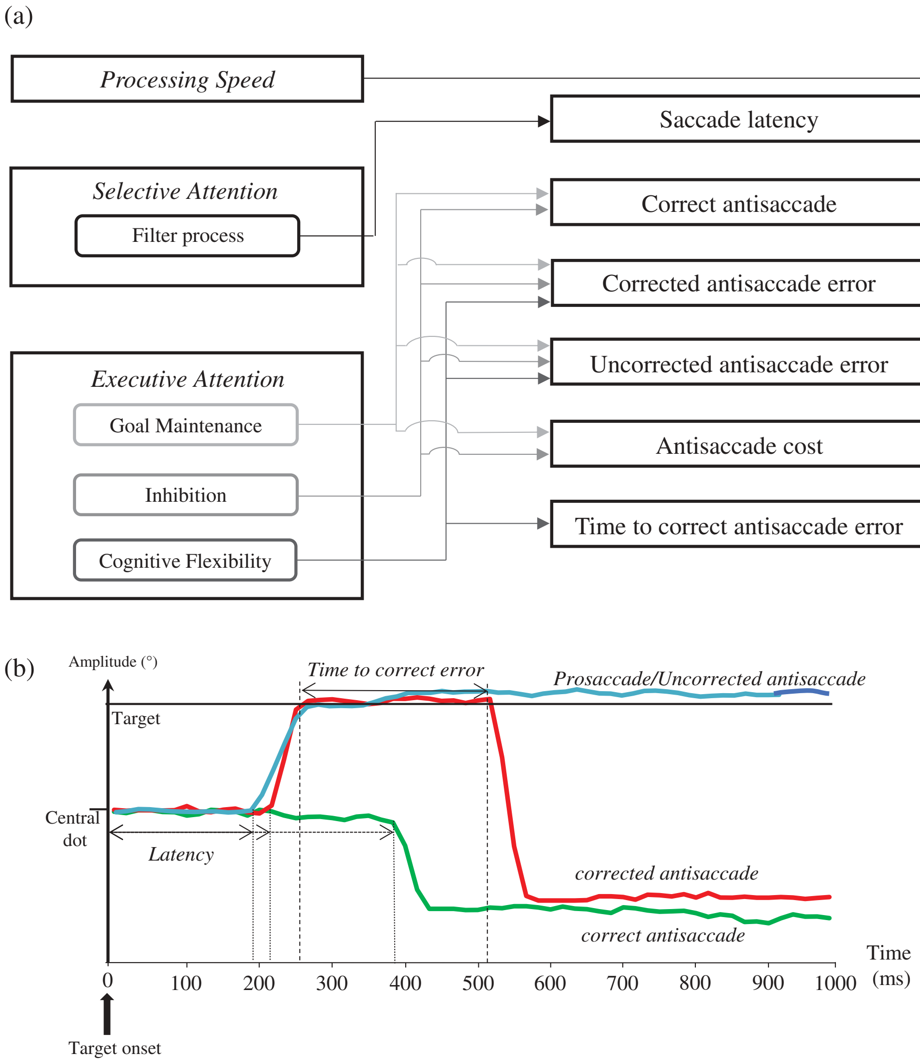

Figure 4. (a) Schematic representation of the cognitive processes involved in saccadic eye movement parameters, as suggested by the present study. (b) Example of saccade recordings with illustrations of saccadic eye movement parameters. [To view this figure in color, please see the online version of this journal.]

Kapoula, 2006; Yang et al., 2006). We also found an increase in the time to correct saccade in $OA_{>65}$ in comparison with YA and $OA_{<65}$. Interestingly, AS parameters (i.e., the proportion of correct and uncorrected AS and the time to correct AS errors) were higher in $OA_{>65}$ than in $OA_{<65}$ and YA but did not differ between $OA_{<65}$ and YA. Conversely, the overlap–step ratio was higher in YA than in both $OA_{>65}$ and $OA_{<65}$ but did not differ between the two older adult groups.

The general increase in latency in $OA_{>65}$ and $OA_{<65}$ group suggested that, regardless of the conditions and the tasks, older adults had a decline in processing speed affecting saccade triggering. The positive correlations found between latency, age, and information processing speed measures belonging to the neuropsychological tests (i.e., TMTA and Stroop W and C) provide another support for the relationship between latency and processing speed. Moreover, the latency increase in $OA_{<65}$ group in comparison with the YA group, and in $OA_{>65}$ group in comparison with the $OA_{<65}$ group, is in agreement with some studies demonstrating that saccadic latency gradually increases after 40 years of age (Litvinova et al., 2011; Munoz et al., 1998). Munoz et al. (1998) noted that the brainstem seems to be free of age-related neurodegenerescence. The neuronal degeneration and hypometabolism found in the non-demented elderly cortex may explain this decline in processing speed (Bakkour, Morris, Wolk, & Dickerson, 2013; Chételat et al., 2013; Dennis & Cabeza, 2008; Kapoula et al., 2010; Salat, Kaye, & Janowsky, 2001; Yang & Kapoula, 2006).

As regards our other latency measure of gap and overlap effect, differences found between older and younger adults in both PS and AS errors provide critical data regarding the role of selective attention. Overall, the latency in our three groups displayed similar patterns of results: lowest latency in the gap condition and highest latency in the overlap condition. These results are in agreement with previous findings (Eenshuistra et al., 2004; Munoz et al., 1998; Peltsch et al., 2011; Yang & Kapoula, 2006; Yang et al., 2006). However, if we examine the size of the gap and the overlap effects (computed in reference to the step condition), our older and younger groups did not have the same behavior. As expected, we found that younger adults displayed a higher overlap–step ratio than the two older groups, except for correct AS latency. In contrast, concerning the gap effect, we found similar results in the different age groups for all saccadic latencies.

The hypothesis of a decline in selective attention in aging (Zanto & Gazzaley, 2014) may provide an explanation for these results. In fact, in the overlap condition, the instruction requires participants to keep their gaze on the central dot. If selective attention is efficient, the appearance of a peripheral target leads to attentional capture delayed by the attentional focus on the central dot (Pratt et al., 2006). If selective attention is less efficient, the appearance of a peripheral target should lead to faster attentional capture (the attentional focus on the central dot being reduced). The decline of selective attention with aging results in an increased risk for attentional capture by peripheral stimulation (as evidenced by a reduction of overlap effect in $OA_{(<65)}$ and $OA_{(>65)}$ when they made PS or AS errors). It is noteworthy that the reduction of the overlap effect was not found in the AS task when older adults made a correct AS. Performing a correct AS requires efficient controlled attention.

Concerning specifically AS parameters and their relationship with executive attention, we hypothesized that alteration of executive attention in older adults (Braver & West, 2008) should lead to higher AS cost, lower proportion of correct AS, and higher proportion of uncorrected AS for $OA_{>65}$ than YA and $OA_{<65}$. $OA_{>65}$ should also spend more time to correct AS errors when they succeed in correcting them, in comparison with YA and $OA_{<65}$. Our results seem to support that hypothesis. The $OA_{(>65)}$ group had a higher AS cost than YA and $OA_{<65}$ groups and only the Stroop CW_i (i.e., controlled attention capacity measures) was a predictor of, and correlated with, the AS cost. Making a correct AS implies the goal maintenance and the inhibition of the saccadic triggering toward the target. We suggest that the mobilization of these two executive attention components leads to a high cognitive demand in older adults, which increases the “decision time” needed to trigger a correct AS.

The decline of executive attention efficiency in older adults could also explain why they had fewer correct AS than YA and $OA_{(<65)}$ groups. In fact, it is possible that saccades were more frequently triggered toward the target because older adults failed to keep effective executive attention throughout the entire AS task. The negative correlations found between the proportion of correct AS and the time to perform TMTB, as well as the time to perform Stroop CW add an argument for the involvement of executive attention in the AS task. Interestingly, the proportion of correct AS was also correlated with the free recall of the FCRT, which can reflect the contribution of the executive function (because retrieving the learned words requires an active memory search).

We also supposed that the capacity to correct, and the time to correct, AS errors reflect cognitive flexibility ability, a third component of the executive attention (Miyake et al., 2000). The proportion of corrected, and the time to correct, AS errors were correlated with the Stroop CW index and the TMTB, which are also the best predictors of these SEM parameters, suggesting the involvement of executive attention, especially cognitive flexibility, in the correction of AS errors. The alteration of executive attention in older adults could reduce the ability to correct the AS error leading to a higher proportion of uncorrected AS errors in $OA_{(>65)}$ in comparison with YA and $OA_{(<65)}$. Furthermore, the decline of cognitive flexibility could also lead $OA_{(>65)}$ adults to take more time to correct AS errors than YA and $OA_{(<65)}$ adults. This point on aging and SEMs has poorly been studied in the literature and the time given to correct AS errors should be better taken into account in the future.

Taken together, our data suggest that aging affects SEMs in PS and AS tasks differently. We found an increase in saccade latency in both PS and AS in $OA_{(>65)}$ and, to a lesser extent, in $OA_{(<65)}$. The ability and the time needed to trigger a correct saccade, as well as the ability to correct AS errors, were altered only in $OA_{(>65)}$ group. These data are coherent with the idea of a differential decline of cognitive process (Borella et al., 2008). Moreover, our findings on the gap–overlap effects improve our knowledge regarding the impact of aging on cognitive decline: the ability to suppress attentional capture seems to be early altered in aging. Indeed, both $OA_{(<65)}$ and $OA_{(>65)}$ had lower overlap–step ratio than YA whereas there was no difference between $OA_{(<65)}$ and $OA_{(>65)}$. However, our study as well as all other studies on aging cited in this paper were cross-sectional. Complementary longitudinal data are needed to specify the dynamics of the phenomena under study.

The neuropsychological tests used in our experiment were chosen because they are the most commonly used in neuropsychological examination in the elderly and they are relatively quick to administer. Although they allowed us to rule out potential pathological cognitive impairments and to show close relationships between SEM parameters, cognition and aging, one possible limitation of the current study is that some of these tests were relatively simple for our population. For instance, the lack of a clear relationship between SEMs and FDS–BDS, as well as the lack of significant differences between younger and older adults in these neuropsychological tests could be due to the weak involvement of working memory process in these tests. This is coherent with the slight age effect on simple span tasks reported in the literature (Braver & West, 2008; Bopp & Verhaeghen, 2005). However, other tests used in the present study such as the Stroop test, the TMTB, or the FR of the FCRT have suggested that executive attention components was altered in older adults. Investigations using more complex working memory tasks should better highlight and clarify the specific relationship between SEMs and working memory.

Our results are in accordance with imagery studies indicating that the frontal areas – particularly the DLPFC – are involved in attentional control, decision processing, and also play a key role in the performances in PS and AS tasks (Domagalik et al., 2012; Matsuda et al., 2004; McDowell et al., 2008; Munoz & Everling, 2004; Pierrot-Deseilligny et al., 2004, 2003). The reported alterations of the SEMs in the elderly, driven by a decline of these cognitive processes, are also coherent with a gradually anterior–posterior neuronal degeneration and decrease in glucose metabolism found in frontal areas in this population (Bakkour et al., 2013; Chételat et al., 2013; Dennis & Cabeza, 2008; Salat et al., 2001). Future research using imagery technology should contribute to offer a more integrated view of neural-cognitive-oculomotor changes that characterize aging.

The present experiment demonstrated that the impact of aging on SEM depends on specific cognitive factors. Our data suggested that the general latency decrease is mainly related to a general decline of processing speed. Moreover, the alteration of executive attention plays a key role in the reduced capacities to control and correct saccades. Close relationships between neuropsychological measures of cognitive flexibility, inhibition, and saccadic parameters supported these conclusions, especially in the AS task. We also demonstrated that the contrast between gap–step and overlap–step conditions can better differentiate gap effect from overlap effect than the merely gap–overlap difference and, therefore, help detect selective attention deficit in older adults. Our findings, together with those of previous studies cited above, should hopefully be useful to provide a better understanding of the relationships between SEM modifications and age-related decline of specific cognitive functions.

Acknowledgments

The authors are most grateful to Richard Medeiros – Medical Editor, Medical Editing International for editing the revised version of the manuscript.

Disclosure statement

No potential conflict of interest was reported by the authors.

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