AMERICAN PSYCHOLOGICAL ASSOCIATION

Journal of Experimental Psychology: General

ISSN: 0096-3445

2023, Vol. 152, No. 12, 3403–3417
https://doi.org/10.1037/xge0001458

When Do We Become More Distractible? Progressive Evolution of Different Components of Distractibility From Early to Late Adulthood

Roxane S. Hoyer, Oussama Abdoun, Mégane Riedinger, Romain Bouet, Alma Elshafei, and Aurélie Bidet-Caulet
Lyon Neuroscience Research Center, INSERM, CNRS, Université Claude Bernard Lyon 1, Université de Lyon

Distractibility determines the propensity to have one's attention captured by irrelevant information; it relies on a balance between voluntary and involuntary attention. We report a cross-sectional study that uses the competitive attention test to characterize patterns of attention across the adult life span from 21 to 86 years old. Several distractibility components were measured in 186 participants distributed within seven age groups. Results indicate that distractibility components follow distinct trajectories with aging: Voluntary orienting remains stable from 21 to 86 years old, sustained attention decreases after 30 years old, distraction progressively increases between 26 and 86 years old, and impulsivity is lower in older compared to younger adults. Increased distractibility in older age thus seems to result from a dominance of involuntary over voluntary attention processes, whose detrimental effect on performance is partly compensated by enhanced motor control.

Public Significance Statement

Attention is a multifaceted cognitive function allowing to focus and resist to distraction. While previous works have mostly compared two groups of young and older adults to investigate attention with aging, the present study characterizes the evolutive trajectories of several attention facets in participants from 21 to 86 years old, distributed in seven age groups. The results provide critical information to better understand *how* and *when* attention changes during normal aging. These findings can help the early detection of pathological attention decline, which can be a prodrome of neurodegenerative diseases.

Keywords: distraction, attention, aging, behavior

Supplemental materials: https://doi.org/10.1037/xge0001458.supp

Aging is associated with a failure of attention, specifically the inability to regulate the processing of irrelevant information (see Healey et al., 2008 for a review). Subclinical attention difficulties hamper autonomy and create dependency on others (Ruan et al., 2015). To develop rehabilitation procedures to counteract this loss of autonomy, a prerequisite is to precisely characterize distractibility from early to late adulthood.

Here, we conceptualize "distractibility" as a state determining the propensity to have one's attention captured by irrelevant information, while "distraction" designates the deleterious effect of involuntary attention capture on ongoing behavioral performance. Attention is a multifaceted function and distractibility results from the efficacy of different cognitive components. Distractibility relies on a balance between voluntary and involuntary attention mechanisms, allowing

This article was published Online First August 17, 2023.
Roxane S. Hoyer https://orcid.org/0000-0003-0954-8550
Roxane S. Hoyer is now at CERVO Brain Research Centre, Université Laval.
The authors thank J. Hemmerlin, M. Navarro, and H. Drissi for their help in recruiting and testing participants and A. Blumenthal for her careful reading of the manuscript. The authors also would like to thank all participants. The competitive attention test application is protected by a trademark "CoLeT." The authors developed an application reproducing the test used in this study (protected by a trademark "CoLeT"). The application uses a normative database constructed with the data presented in this article. For this reason, raw data cannot be shared. The codes used to process the data are available on a public repository (https://github.com/RoxaneHoyer/Codes_processing_CAT_data_elderly.git) or upon request by contacting Roxane S. Hoyer. This work was performed within the framework of the LABEX CORTEX (ANR-11-LABX-0042) and the LABEX CeLyA (ANR-10-LABX-0060) of Université de Lyon, within the program "Investissements d'Avenir" (ANR-16-IDEX-0005) operated by the French ANR.

Roxane S. Hoyer served as lead for data curation, formal analysis, visualization, and writing–original draft. Oussama Abdoun served in a supporting role for methodology and writing–review and editing. Romain Bouet served as lead for software and served in a supporting role for writing–review and editing. Alma Elshafei served in a supporting role for writing–review and editing. Aurélie Bidet-Caulet served as lead for funding acquisition and supervision and served in a supporting role for writing–original draft. Roxane S. Hoyer, Alma Elshafei, and Aurélie Bidet-Caulet contributed equally to conceptualization. Roxane S. Hoyer and Aurélie Bidet-Caulet contributed equally to methodology, project administration, and writing–review and editing. Roxane S. Hoyer, Mégane Riedinger, and Alma Elshafei contributed equally to investigation.

Correspondence concerning this article should be addressed to Roxane S. Hoyer, CERVO Brain Research Centre, Université Laval, 2601, Chemin de la Canardière, Québec City, Québec G1J 2G3, Canada. Email: roxane.hoyer@gmail.com

one to focus while staying alert to one's surroundings. Voluntary attention promotes the processing of task-relevant stimuli and is internally driven. Involuntary attention is directed by external stimuli and refers to the capture of attention by task-irrelevant, unexpected, and salient events, leading to distraction. Beyond attention, behavioral distractibility is shaped by arousal and motor control (whose failure induces impulsivity). Attention, arousal, and motor control are underpinned by interconnected brain networks (Aston-Jones & Cohen, 2005; Petersen & Posner, 2012; Posner et al., 1982; Seidler et al., 2010). Distractibility components, particularly orienting and sustained attention (voluntary attention), arousal, distraction (involuntary attention), motor control, and impulsivity, have been mostly studied separately, through the comparison of two age groups (i.e., younger vs. older adults; Andrés et al., 2006; Brodeur & Enns, 1997; Coyne et al., 1978; Davies & Davies, 1975; ElShafei et al., 2020; Greenwood et al., 1993; Horváth et al., 2009; Iarocci et al., 2009; Jackson & Balota, 2012; Leiva et al., 2014, 2016; Mager et al., 2005; Olk & Kingstone, 2015; Parasuraman et al., 1989; Parmentier & Andrés, 2010). These studies were successful in identifying *what* changes in attention abilities occur between early and late adulthood, but not *when* these changes take place during aging. Furthermore, they yielded inconsistent results: Methodologically, this might be explained by the use of broad age ranges within the to-be-compared groups of participants. These contradictory findings are detailed in the followings.

The capacity to orient voluntary attention has been found either unchanged (Greenwood et al., 1993; Iarocci et al., 2009; Olk & Kingstone, 2015) or decreased (Brodeur & Enns, 1997; see also Erel & Levy, 2016 for a review) with aging. The ability to sustain voluntary attention over time (also known as "vigilance") has been found to be deteriorating from middle to late adulthood (Berardi et al., 2001; Davies & Davies, 1975; Fortenbaugh et al., 2015; Jackson & Balota, 2012; Parasuraman et al., 1989; Petton et al., 2019), or to improve with aging (see Vallesi et al., 2021 for a review).

The results on distraction (quantified as increased reaction times [RTs] or reduced accuracy to targets preceded by a salient sound; Andrés et al., 2006; Bidet-Caulet et al., 2015; Escera et al., 2000; Näätänen, 1992; Wetzel & Schröger, 2014) are also mixed. Some studies found increased distraction (Andrés et al., 2006; Berti et al., 2013; ElShafei et al., 2020; Leiva et al., 2014, 2016; Parmentier & Andrés, 2010), while others found distraction unchanged (Horváth et al., 2009; Mager et al., 2005) in older compared to younger adults.

Salient events, such as distractors, can also result in a behavioral benefit in some tasks (reduced RTs to targets preceded by a salient sound; Andrés et al., 2006; Bidet-Caulet et al., 2015; Masson & Bidet-Caulet, 2019; Max et al., 2015; Näätänen, 1992; Wetzel et al., 2012). This behavioral facilitation has been attributed to an aspecific increase in cortical responsiveness resulting from a transient increase in phasic arousal (Masson & Bidet-Caulet, 2019) mediated by the locus coeruleus–norepinephrine system (LC–NE; Aston-Jones & Cohen, 2005). While this link between behavioral facilitation and a phasic increase in LC–NE activity still needs to be demonstrated in humans, it is supported by pupil dilation data (Wetzel et al., 2016), an indirect measure of the LC–NE activity. Interestingly, the LC activity is altered with aging (Dahl et al., 2022), while at the behavioral level, the phasic arousal increase triggered by distractors has been found similar in young and older adults (Andrés et al., 2006; ElShafei et al., 2020; Parmentier & Andrés, 2010).

Changes in voluntary attention orienting and distraction, as well as phasic arousal, may urge one to impulsively respond to irrelevant events. Motor control can also be considered as a distractibility component since it plays a role in the emergence of impulsive behaviors by supporting the ability to stop an ongoing response. Impulsivity is another component of distractibility and refers to the tendency to act before having fully analyzed a situation, without regard for the consequences of the act to oneself or to others (Barratt & Patton, 1983). Impulsivity has been found to be increased (Coyne et al., 1978; Maylor et al., 2011; Nielson et al., 2002) or unchanged (Hong et al., 2014; Hsieh et al., 2016; Lin & Cheng, 2020; Paitel & Nielson, 2021) in older adults compared to younger ones (see also Rey-Mermet & Gade, 2018 for a review).

Using the competitive attention test (CAT; Bidet-Caulet et al., 2015), which provides simultaneous measures of several attention facets, recent studies have investigated the brain origins of distractibility in 60- to 75-year-old adults (ElShafei et al., 2020, 2022). Their magnetoencephalographic findings suggest that elderly have altered top-down attention mechanisms (ElShafei et al., 2020, 2022). In particular, increased distractibility in older adults is associated with reduced top-down inhibition of irrelevant information, a brain mechanism supported by the lateral prefrontal cortex (Amer et al., 2016; Colcombe et al., 2005; ElShafei et al., 2020, 2022). From a theoretical perspective, this is aligned with the inhibitory deficit (Hasher & Zacks, 1988) and the frontal aging (West, 1996) hypotheses. However, it remains to elucidate when precisely during aging this prefrontal-related decline starts impacting attention performance.

Using the CAT, the present study aims to outline the evolution of the cognitive components contributing to distractibility from 21 to 86 years, in a large sample of participants ($N = 191$). This paradigm provides behavioral measures of voluntary orienting, sustained attention, distraction, phasic arousal, as well as motor control and impulsivity (Bidet-Caulet et al., 2015; Hoyer et al., 2021). Our general hypothesis was that distractibility (the propensity to have one's attention captured by irrelevant information) would increase with age. As previous results on the distractibility components with aging were mixed, no specific hypotheses were formulated regarding their evolution from early to late adulthood. This study was thus mainly exploratory.

Method

Participants

In total, 191 subjects from diverse socioeconomic statuses (SES; small employers and self-employed, never worked or long-term unemployed, managerial and professional occupation, lower supervisory and technical occupations, semiroutine and routine occupations, intermediate occupations, and retired; see Figure S1 in the online supplemental materials) who spoke French fluently participated in the study. Participants were recruited using email lists and via several senior clubs. They had to fulfill the following inclusion criteria: corrected-to-normal hearing (two participants wore hearing aid and confirmed that it caused them no discomfort to listen to different sounds during the experiment), normal or corrected-to-normal vision, no neurological or psychiatric disorders, and no medication affecting the central nervous system taken during the 24 hr preceding the testing session. Race, ethnicity, and gender data were not

Table 1
Characteristics of the Population Sample

Age range in years	Number of participants included	Mean age in years	Biological sex: Female (%)	Biological sex: Male (%)	Handedness: Right (%)	Handedness: Left (%)	Handedness: Ambidextrous (%)	Mean education	Auditory threshold: Right ear	Auditory threshold: Left ear	Testing period: Morning (%)	Testing period: Afternoon (%)
21–25	32	23.3 ± 0.3	50.0	50.0	84.4	15.6	0.0	4.1 ± 0.2	25.8 ± 2.2	26.7 ± 2.2	50.0	50.0
26–30	24	27.0 ± 0.3	58.3	41.7	87.5	8.3	4.2	3.6 ± 0.3	31.7 ± 2.5	30.9 ± 2.5	25.0	75.0
31–40	25	35.2 ± 0.5	60.0	40.0	80.0	20.0	0.0	4.2 ± 0.2	31.1 ± 2.1	30.6 ± 2.0	28.0	72.0
41–50	27	46.1 ± 0.6	74.1	25.9	88.9	7.4	3.7	3.7 ± 0.2	28.4 ± 2.4	28.7 ± 2.0	29.6	70.4
51–60	25	55.8 ± 0.6	56.0	44.0	92.0	4.0	4.0	3.1 ± 0.3	32.6 ± 2.5	33.6 ± 2.7	44.0	56.0
61–70	25	65.7 ± 0.6	60.0	40.0	88.0	0.0	12.0	3.1 ± 0.3	35.6 ± 2.5	36.2 ± 2.5	44.0	56.0
71–86	28	78.4 ± 0.9	85.7	14.3	82.1	7.1	10.7	2.0 ± 0.3	42.4 ± 1.4	42.8 ± 1.9	21.4	78.6

Note. Detailed samples, mean age in years, biological sex, handedness, mean education level (0 = *no diploma*, 1 = *vocational certificate obtained after the ninth grade*, 2 = *high school diploma*; 3 = *12th-grade/associate's degree*; 4 = *bachelor's degree*; 5 = *master's degree and further*), thresholds of auditory perception in dBA, and testing period by age range (± standard error of the mean [*SEM*]).

collected; only the biological sex (options given: male or female) was collected through a sociodemographic questionnaire. The samples selected for the study were of convenience: Participants were recruited until each of the age groups included a minimum of 20 participants (see Table 1). We mainly used age ranges of 10 years. Before 30 years of age, brain gray and white matters are still maturing, particularly in frontal areas (e.g., Tamnes et al., 2010; Yeatman et al., 2014): Young adults were thus divided into smaller age groups, 21- to 25- and 26- to 30-year-olds. Moreover, participants with more than 71 years of age were pooled in one age range; this population was difficult to recruit because older participants were often not willing to do the experiment or fell into the exclusion criteria. Seven age ranges were therefore defined as follows: 21–25, 26–30, 31–40, 41–50, 51–60, 61–70, and 71–86 years of age. Participants in each age group were selected to match, as best as possible, the other age groups in biological sex, handedness, and education. Data from 20 participants (out of 32) from the 21–25 years age group used in this manuscript were also analyzed in Hoyer et al. (2021).

Data from five participants were excluded from the analysis, due to either below-chance performance (correct trial percentage <50% in the no distractor condition; see Figure 1: $n = 2$) or technical issues ($n = 3$). A total of 186 subjects (86% right-handed, 9% left-handed, 5% ambidextrous; 63% female and 37% male; 21–86 years old) were included in the analysis (see Table 1 for details by age ranges). All participants gave written informed consent. This study was conducted according to the Helsinki Declaration, Convention of the Council of Europe on Human Rights and Biomedicine, and the experimental paradigm was approved by the French ethics committee Comité de Protection des Personnes. Note that, to improve readability, "yo" instead of "years-old" or "year-olds" is used in the Method and Results sections when referring to the participants' age ranges.

Stimuli and Task

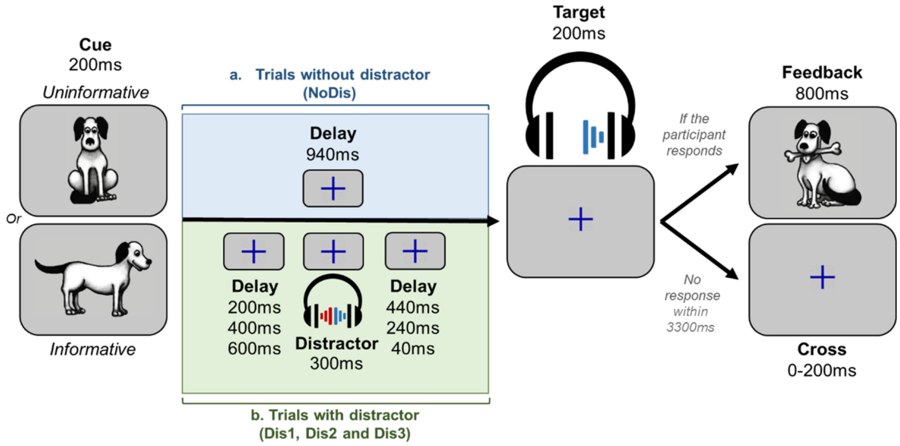
A detailed description of the task can be found in a previous study (Hoyer et al., 2021). In the no distractor condition (NoDis: 50%), a visual cue (200 ms duration) was followed, after a 940-ms delay, by a target sound (200 ms duration; Figure 1a). The cue was a dog facing left or right (informative: 75%), or to the front (uninformative: 25%). The target sound was a dog bark monaurally presented in headphones. The dog facing left or right (informative) was followed by the target sound in the left (37.5%) of right (37.5%) ear, respectively; the facing-front dog (uninformative) was followed by the target sound in the left (12.5%) or right (12.5%) ear. In distractor condition (Dis: 50%), a binaural distracting sound (300 ms duration, 18 different ringing sounds distributed across three blocks) was played during the 940-ms delay (Figure 1b): This sound could be played at three different times—distributed equiprobably—during the delay: 200 ms (Dis1), 400 ms (Dis2), and 600 ms (Dis3) following the cue offset. The target sound was presented at 15 dB Sensation Level (SL) (around 37.5 dBA) and the distracting sound at 35 dB SL (around 67.5 dBA) in headphones. The distractor was played louder and longer than the target in order to induce attention capture and activate the ventral attention brain network. Different distractor timings were used (a) to limit predictability by precluding participants from using the distractor as a second cue and (b) to dissociate the facilitation and detrimental effects of distractors on behavioral performance (Masson & Bidet-Caulet, 2019). Cue categories (informative and uninformative) and target categories (left and right) were equally distributed through trials with and without distracting sounds. Overall, the task included 144 trials: 72 NoDis and 72 Dis trials. In each condition, NoDis and Dis, 54 trials were informative, and 18 uninformative. In Dis condition, 24 trials comprised a Dis1, 24 a Dis2, and 24 a Dis3.

Participants were instructed to focus their attention on the cued side and to press a key as fast as possible when they heard the target sound. Visual feedback (800 ms duration) was displayed when participants detected the target within 3,300 ms of its onset, followed by a rest period (intertrial interval: 1,700–1,900 ms). If the participant did not respond in time, the fixation cross was displayed for an additional randomized delay (100–300 ms).

Procedure

Participants were tested individually or in small groups (of two or three) in a quiet room. Participants were able to choose the time of the day they preferred but were always tested between 9 a.m. and 12 p.m. (morning) or between 1 p.m. and 5 p.m. (afternoon). During the task, participants were seated in front of a laptop (approximately 50 cm from the screen) that presented pictures and sounds and recorded behavioral responses using Presentation software (Neurobehavioral Systems, Albany, California, United States). Auditory stimuli were played through headphones. First, for each

Figure 1
Protocol



Note. (a) In uninformative trials, a facing-front dog was used as a visual cue, indicating that the target sound would be played in either the left or right ear. In informative trials, a dog visual cue facing left or right indicated in which ear (left or right, respectively) the target sound will be played. If the participant gave a correct answer within the 3,300 ms posttarget offset, feedback (800 ms duration) was displayed. (b) In trials with distractors, the task was similar, but a binaural distracting sound—such as a phone ring—was played during the cue-target delay. The distracting sound could equiprobably onsets at three different times: 200, 400, or 600 ms after the cue offset. NoDis = no distractor condition; Dis = distractor condition. See the online article for the color version of the figure.

participant in each ear, the auditory threshold was determined for the target sound using the Bekesy tracking method. This resulted in an average target threshold across subjects of 32.5 dBA (see Table 1 for details by age range). Then, participants received verbal instructions and performed a short training of the task followed by three 4-min blocks of 48 pseudorandomized trials each. The experimental session lasted around 30 min.

Measure Parameters

We used a custom MATLAB program to preprocess behavioral data. RT limits for responses to be categorized as correct were computed in each age range to take into account the overall age-related slowing (Salthouse, 1996, 2017). The shortest RT for a correct response (RT lower limit) was calculated from the RT distribution of each age range (150 ms in the 21–25, 26–30, 31–40, 41–50, and 51–60 yo, and 200 ms in the 61–70 and 71–86 yo; see Figure S2 in the online supplemental materials). For each participant, the longest RT for a correct response (RT upper limit) was calculated from all RT > 0 ms using the Tukey method of leveraging the interquartile range. Based on the lower and upper RT limits, responses can be divided into three categories: (a) Responses before the RT lower limit were considered as false alarm responses; (ii) responses between the lower and the upper RT limit were considered as correct responses; and (iii) responses after the RT upper limit were considered as late responses (see Figure 2).

Responses before the RT lower limit can occur (see Figure 2): in response to nontarget stimuli (cue and distractor responses) and reflect impulsivity; randomly when there is no stimulus (random response) and index motor control failures; before the shortest correct RT (anticipated responses) and reflect an error in anticipating the time of target presentation. Missed responses were counted when no other response was given during the entire trial. Finally, RT and standard deviation of reaction times (RT *SD*) were analyzed from the positive RT only (responses made after the target onset); these measures are thus named RT_+ and RT_{+SD} in the following. In summary, a total of nine behavioral measures were considered in this study: late, missed, cue, random, distractor, and anticipated responses, as well as RT_+, normalized reaction times (RT_{+norm}), and RT_{+SD} (see Table 2 for more details). To the best of our knowledge, no other study has used an age-dependent threshold to dissociate early responses (false alarms) and correct responses. Here, RT_+ analysis included all positive RT, and not only RT for correct responses, to provide a measure comparable to those used in previous research. Across the overall sample, the total average of trials with positive RT (RT_+ and RT_{+norm}) was 69.7 ± 0.4 (min: 38, max: 72) in NoDis, 22.3 ± 0.2 (min: 10, max: 24) in Dis1, 22.5 ± 0.2 (min: 12, max: 24) in Dis2, and 22.8 ± 0.2 (min: 12, max: 24) in Dis3 conditions.

Statistical Analysis

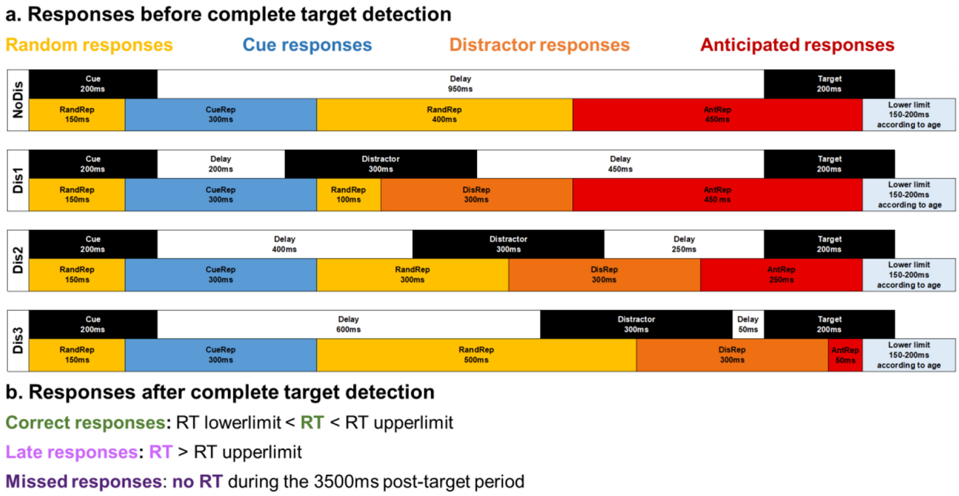
To estimate tendencies linked to the behavioral measures at the single trial level, we used generalized linear mixed models (GLMM) in a frequentist approach; models were adapted to the data distribution (i.e., Gaussian for RT-related measures, binomial for response types). In order to test the similarity between groups, Bayesian statistics were used. In contrast to Frequentist statistics, Bayesian analyses allow one to assess the credibility of both the alternative and null hypotheses.

Sample Characteristics

To confirm that our sample population was similarly distributed across age ranges in block order, biological sex, handedness, SES,

Figure 2

Timeline for the Response Categorization During the CAT Trials



Note. (a) From top to bottom: NoDis, Dis1, Dis2, and Dis3 conditions. The superior row depicts the timing of the task-related events (cue, distractor, and target); the inferior row shows the category in which the behavioral response is assigned based on its timing. Cue (CueRep), distractor (DisRep), anticipated (AntRep), and random (RandRep) responses are performed before the shortest correct RT. (b) Summary of the method used for estimating correct, late, and missed responses. CAT = competitive attention test; NoDis = no distractor condition; Dis = distractor condition; CueRep = cue responses; DisRep = distractor responses; AntRep = anticipated responses; RandRep = random responses; RT = reaction time; no RT = no reaction time. See the online article for the color version of the figure.

and testing periods (morning or afternoon), we performed Bayesian contingency table tests. Specifically, we performed a Bayesian analysis of variance (ANOVA) on the education level with AGE as between-subject factor to investigate potential differences in education across age ranges. Bayesian statistics were performed using JASP software (JASP—A Fresh Way to Do Statistics, 2021; Version 0.14.1). We reported Bayes factor (BF_{10}) as a measure of evidence in favor of the null hypothesis (BF_{10} 0.33–1, 0.1–0.33, 0.01–0.1, and lower than 0.01: weak, positive, strong, and decisive evidence, respectively) and in favor of the alternative hypothesis (value of 1–3, 3–10, 10–100, and more than 100: weak, positive, strong, and decisive evidence, respectively; M. D. Lee & Wagenmakers, 2013).

Behavioral Data Analysis

To analyze behavioral data at the single trial level, we used GLMM (Bates et al., 2015). The variability between subjects in raw performance was modeled by defining by-subject random intercepts.

To assess the impact of the manipulated task parameters (cue information and distractor type) and participant age range, on each type of behavioral measure (RT_{+}, RT_{+norm}, RT_{+SD}, late, missed, cue, distractor, anticipated, and random responses; see Table 2 for more details), we analyzed the influence of different fixed effects and their interaction (specified in Table 3): the between-subject factor AGE (seven levels: 21–25, 26–30, 31–40, 41–50, 51–60, 61–70, and 71–86 yo), the within-subject factor CUE (two levels: informative and uninformative), and the within-subject factor DISTRACTOR (four levels: NoDis, Dis1, Dis2, and Dis3). A summary of the data and factors used in statistical modeling can be found in Table 3. Because of the different timings for categorizing erroneous responses (see Figure 2), and the low proportion of the cue, random, and distractor responses, we did not consider the CUE and DISTRACTOR factors in analyses of these measures and only focused on the AGE effect. Despite a more important proportion of late responses, the last procedure was also used for this measure: Analyses of late responses and RT_{+} are mirroring each other, we thus only focused on the AGE effect on late responses in NoDis to investigate short-term sustained attention changes with aging. For anticipated and missed responses, we considered the within-subject factor DISTRACTOR in the analysis as these responses have previously been identified as good markers of distraction and impulsivity in children and young adults (Hoyer et al., 2021).

Frequentist statistics were performed in R Version 3.4.1 using the lme4 (Bates et al., 2015) and car (Fox & Weisberg, 2018) packages. Both fixed and random factors were considered in statistical modeling. Wald chi-square tests were used for fixed effects in linear mixed-effects models (Fox & Weisberg, 2018). The fixed effect represents the mean effect across all subjects after accounting for variability. We considered the results of the main analyses significant at $p < .05$.

When we found a significant main effect or interaction, Post hoc honestly significant difference (HSD) tests were systematically performed using the R emmeans package (Version 1.6.3). p Values were considered as significant at $p < .05$ and were adjusted for the number of comparisons performed. More precisely, to avoid increased Type I error when multiple comparisons were performed, the p value of the Tukey HSD test was adjusted using the Tukey method for comparing the given number of estimates.

To calculate effect sizes, we used the R effectsize package (Ben-Shachar et al., 2020): For linear mixed models with Gaussian

Table 2

Measure Names, Detailed Criteria for Responses Categorization in the CAT Trials, and Associated Measured Constructs

Response type	Description	Response interpretation
Behavioral measurements of attention effects on target processing		
RT_+	RT of positive response times	Overall processing speed influenced by cognitive aging
RT_{+norm}	Positive reaction times (single trial)/mean of positive reaction times (intrasubject)	Overall processing speed without the cognitive aging influence
Detrimental effect of distractor	Mean RT_{+norm}: NoDis − Dis1	Phasic arousal effect *Index of phasic arousal due to the presence of a distractor*
Facilitation effect of distractor	Mean RT_{+norm}: Dis3 − Dis1	Distraction effect *Index of attention capture by a distractor*
RT_{+SD}	Mean *SD* of positive response times in the NoDis condition for each block separately	Variability in processing speed *Long-term sustained attention*
Late responses	Percentage of responses in the NoDis condition during the period starting from the RT upper limit to 3,300 ms	Slow processing error *Failure of short-term sustained attention*
Missed responses	Percentage of trials without any response made during the entire trial duration up to 3,300-ms posttarget	Omission *Lapse of sustained attention in no distractor condition Distraction in distractor condition*
Behavioral measurements of attention effects on target expectancy		
Cue responses	Percentage of [incorrect or false alarm] responses performed during the 150- to 450-ms period postcue onset	Erroneous response to the cue *Impulsivity*
Distractor responses	Percentage of responses performed during the 150- to 450-ms period postdistractor onset	Erroneous response to the distractor *Impulsivity*
Anticipated responses	Percentage of responses performed: In NoDis and Dis1: from 300 ms pretarget to the RT lower limit posttarget In Dis2: from 150 ms pretarget to the RT lower limit posttarget In Dis3: from 100 ms posttarget to the RT lower limit posttarget	Erroneous response in anticipation of the target *Impulsivity*
Random responses	Percentage of responses performed in the remaining periods of the trials: In NoDis: during the 450- to 850-ms period postcue onset In Dis1: during the 450- to 550-ms period postcue onset In Dis2: during the 450- to 750-ms period postcue onset In Dis3: during the 450- to 950-ms period postcue onset	Erroneous responses outside of response parameters above

Note. CAT = competitive attention test; RT_+ = reaction times; RT_{+norm} = normalized reaction times; RT_{+SD} = standard deviation of reaction times; NoDis = no distractor condition; Dis = distractor condition.

distribution (RT), we computed the omega squared coefficient and interpreted it using Cohen's guidelines (Cohen, 1992); for GLMMs using binomial distribution (response types), we computed the log *OR* and interpreted it using Cohen's guidelines (Cohen, 1988). In the Results section, we reported the 95% confidence intervals (CIs) as a measure of uncertainty; error bars within plots represent quantiles between 5% and 95%.

RT_+ and RT_{+norm}. To investigate the effect of cognitive aging on the global response speed, raw RT_+ were fitted to a linear model with AGE only as between-subject factor. To avoid analysis bias due to the typical slowing affecting RT during aging (see Leiva et al., 2021 for more details), further analyses were performed on raw RT_{+norm} at the single trial level using individual mean RT_+ (at the participant level: RT_+ single trial/mean RT_+). Then RT_{+norm} were fitted to a linear model, with AGE as between-subject factor, and CUE and DISTRACTOR as within-subject factors. For post hoc analysis of the DISTRACTOR × AGE interaction on RT_{+norm}, we planned to analyze two specific measures of the distractor effect: the distractor occurrence (i.e., facilitation effect of distractor; RT_{+norm} in NoDis − RT_{+norm} in Dis1) and the distractor position (i.e., detrimental effect of distractor; RT_{+norm} in Dis3 −s RT_{+norm} in Dis1). Based on previous results (Bidet-Caulet et al., 2015; Hoyer et al., 2021; Masson & Bidet-Caulet, 2019), these differences can be, respectively, considered as good approximations of the phasic arousal and distraction effects triggered by distracting sounds (see Figure 3).

To ensure the reliability of the planned post hoc analysis based on the aforementioned RT_{+norm} differences (facilitation and detrimental effects of distractor), we also performed post hoc pairwise comparisons of RT_{+norm} in the different combinations of distractor conditions. A table presenting these results (consistent with the RT_{+norm} difference results) can be found in Tables S3-1 and S3-2 in the online supplemental materials.

Other Measures. RT_{+SD} were analyzed with the fixed factors AGE as between-subject factor and BLOCK as within-subject factor.

Response types were fitted to a linear model with binomial distribution without transformation. Missed responses were fitted to a linear model with AGE as between-subject factor and DISTRACTOR as within-subject factor (see Table 3). Late, cue, random, and distractor responses were fitted to a linear model with AGE as between-subject factor (see Table 3). Anticipated responses were fitted to a linear model with fixed factors AGE as between-subject factor and DISTRACTOR as within-subject factor

Table 3
Main Statistical Analyses According to Behavioral Response Types

Response type	Condition(s) used for response type calculation	Fixed factor(s): Between subjects	Fixed factor(s): Within subjects	Random factor	Distribution fitting
RT_+	NoDis and Dis1 and Dis2 and Dis3	Age		Subject	Gaussian
RT_{+norm}	NoDis vs. Dis1 vs. Dis2 vs. Dis3	Age	Cue, distractor	Subject	Gaussian
RT_{+SD}	NoDis	Age	Block	Subject	Gaussian
Late responses	NoDis	Age		Subject	Binomial
Missed responses	NoDis vs. Dis1 vs. Dis2 vs. Dis3	Age	Distractor	Subject	Binomial
Cue responses	NoDis and Dis1 and Dis2 and Dis3	Age		Subject	Binomial
Distractor responses	Dis1 and Dis2 and Dis3	Age		Subject	Binomial
Anticipated responses	NoDis vs. Dis1	Age	Distractor	Subject	Binomial
Random responses	NoDis and Dis1 and Dis2 and Dis3	Age		Subject	Binomial

Note. Experimental conditions, factors, and models used as a function of the behavioral measures. Detailed factor levels: distractor = NoDis, Dis1, Dis2, and Dis3; cue = informative and uninformative; block = first, second, and third. RT_+ = reaction times; RT_{+norm} = normalized reaction times; RT_{+SD} = standard deviation of reaction times; NoDis = no distractor condition; Dis = distractor condition.

(see Table 3). Because of the important differences in the duration of the anticipated response windows between distractor conditions (see Figure 2), the GLMM was performed on the NoDis and Dis1 conditions only (same timeframe for anticipated responses in these two conditions).

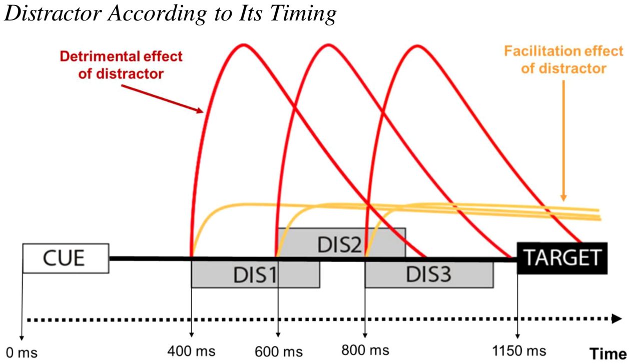
Transparency and Openness

The codes used to build the test are available on a public repository (https://github.com/RoxaneHoyer/Material_CAT.git), or upon request by contacting Roxane S. Hoyer. The codes used to preprocess and process the data are available on a public repository (https://github.com/RoxaneHoyer/Codes_processing_CAT_data_elderly.git), or upon request by contacting Roxane S. Hoyer. For legal reasons, raw data cannot be shared as they are used in a normative database whose copyright is protected.

Results

A summary of the results from the main analyses performed on behavioral data can be found in Table 4.

Figure 3
Schematic Representation of the Different Effects Triggered by the Distractor According to Its Timing



Note. Schematic representation of the facilitation arousal effect and the detrimental distraction effect timings during the CAT trials. CAT = competitive attention test; DIS = distractor condition. See the online article for the color version of the figure.

Population Characteristics

Using Bayesian contingency table tests, we found positive evidence for a similar distribution in biological sex ($BF_{10} = 0.103$) across age ranges. We also observed decisive evidence for a similar distribution in handedness ($BF_{10} = 2.057e^{-6}$) and block order ($BF_{10} = 1.086e^{-8}$) across age ranges. By contrast, we found decisive evidence for a nonuniform distribution in SES characteristics ($BF_{10} = 5.707e^{+25}$), the youngest participants (21–25 yo) being mostly students and the oldest ones (71–86 yo) being mostly retired (see Figure S1 in the online supplemental materials). We also observed strong evidence in favor of a similar distribution of the testing periods across age ranges ($BF_{10} = 0.028$). However, half of the 21–25 yo were tested in the morning, while a larger proportion of 26–86 yo performed the CAT during the afternoon (see Table S4 in the online supplemental materials, for a comparison between results from analyses performed on data acquired during the morning and afternoon, and during the afternoon only). The Bayesian ANOVA carried out on education level showed that mean education decreases with age (for detailed post hoc contrasts, see Table S5 in the online supplemental materials). This decrease in education level with age can be explained by the fact that access to graduate studies has been made easier these last decades (e.g., construction of universities, availability of fellowships, etc.).

RT_+

We observed a main effect of the AGE on RT_+, $\chi^2(6) = 141.0$, $p < .001$ (Figure 4). Tukey post hoc analysis indicated that the 21–30 yo were faster than the 41–86 yo, the 31–40 yo were faster than the 51–86 yo, and finally, the 51–70 yo were faster than the 71–86 yo (see Figure 4 and Table 5 for differences, CIs, and p values). RT_+ thus progressively increases from 31 to 86 years of age.

RT_{+norm}

A main effect of CUE, $\chi^2(1) = 10.34$, $p = .002$ (Figure 5) on RT_{+norm} was observed, indicating that, irrespective of age, participants were faster when the cue was informative (1.000, 95% CI [0.664, 1.010]) rather than uninformative (1.010, [0.994, 1.030]). The interaction CUE × AGE was found nonsignificant, $\chi^2(6) = 8.79$, $p = .186$ (Figure 6a).

Table 4
Results of Main Statistical Analyses

Factor	Speed processing RT_+	Long-term sustained attention RT_{+SD}	Short-term sustained attention Late responses	Sustained attention (NoDis) distraction (Dis) Missed responses	Reactive impulsivity to relevant events Cue responses	Reactive impulsivity to irrelevant events Distractor responses	Proactive impulsivity to irrelevant events Anticipated responses	Motor control Random responses
Age range	$p = 1.000$	$p < .001$***	$p = .062$	$p = .002$**	$p = .705$	$p = .550$	$p = .001$**	$p = .905$
Cue	$p = .001$**							
Distractor	$p < .001$***			$p = .248$			$p < .001$***	
Age Range × Distractor	$p < .001$***			$p = .099$			$p = .463$	
Age Range × Cue	$p = .186$							
Cue × Distractor	$p = .046$							
Age Range × Distractor × Cue	$p = .990$							
Block		$p < .027$*						
Block × Age Range		$p = .477$						

Note. RT_+ = reaction times; RT_{+SD} = standard deviation of reaction times; NoDis = no distractor condition; Dis = distractor condition.
* $p < .05$. ** $p < .01$. *** $p < .001$.

As expected, we did not observe a main effect of AGE on RT_{+norm}, $\chi^2(6) = 0.06$, $p = 1.000$, suggesting that the normalization method we used was appropriate. The main effect of DISTRACTOR on RT_{+norm} was significant, $\chi^2(3) = 2{,}651.87$, $p < .001$ (Figure 5). An AGE × DISTRACTOR interaction was also significant, $\chi^2(18) = 69.52$, $p < .001$. Planned post hoc contrasts (see Table S3-1 and S3-2 in the online supplemental materials, for post hoc pairwise comparisons) were carried out on the different RT effects triggered by the distractor occurrence (see Method section and Figure 3 for more details). Post hoc tests indicated that the 21–25 yo presents an increased NoDis–Dis1 facilitation effect compared to the 26–30 yo, 41–50 yo, 51–60 yo, and 61–70 yo; the 71–86 yo also showed an increased facilitation effect compared to the 41–50 yo and the 51–60 yo (see Figure 6b and Table 6 for differences, CIs, and p values). In addition, the Dis3–Dis1 detrimental effect was increased in the 21–25 yo compared to the 26–30 yo, in the 41–86 yo compared to the 26–30 yo, and in the 61–86 yo compared to the 31–40 yo (see Figure 6c and Table 6 for differences, CIs, and p values). Overall, RT_{+norm} analysis indicates that the facilitation effect of distractor decreases after 25 yo and increases after 60 yo, while the detrimental effect of distractor progressively increases from 26 to 86 years of age.

RT_{+SD}

RT_{+SD} was modulated by the AGE, $\chi^2(6) = 28.46$, $p < .001$ (Figure 7): Post hoc HSD comparisons indicated that the 21–25, 26–30, 31–40, and 51–60 yo had a reduced RT variability compared to the 71–86 yo, and the 26–30 yo also showed less variable RT_+ than the 41–50 yo (see Table 7 for differences, CIs, and p values). We observed a main effect of the BLOCK on RT_{+SD}, $\chi^2(2) = 7.22$, $p = .027$: According to post hoc HSD comparisons, participants had more variable RT_+ in the first compared to the third block (difference [diff.] = 16.7 ms, 95% CI [2.7, 31.4], $p = .021$). There was no AGE × BLOCK interaction, $\chi^2(12) = 11.60$, $p = .477$.

To sum up, RT_{+SD} increases after 30 and 60 years of age. Furthermore, irrespective of age, RT_{+SD} reduces from the first to the third block of the experiment.

Accuracy

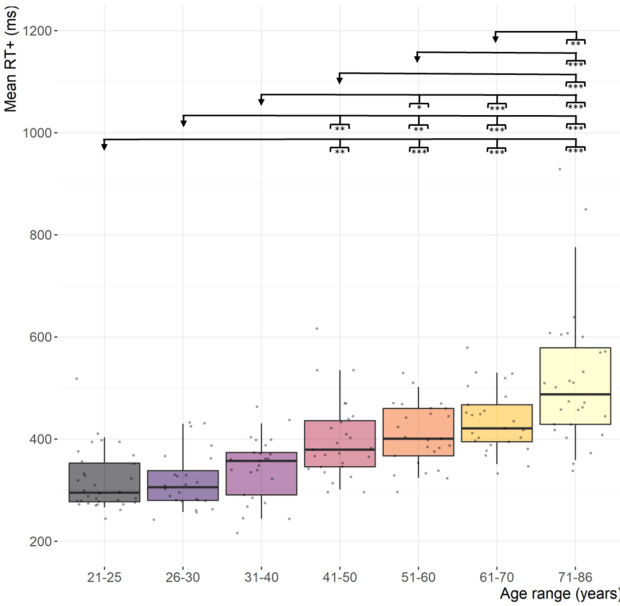
The proportion of the different types of behavioral responses according to age is depicted in Figure 8. The average correct response rate was 87.8%. No main effect of AGE was found for cue responses (total average: 0.2%), distractor responses (total average: 2.5%), random responses (total average: 0.1%), and late responses (total average: 10.3%).

Missed Responses

The rate of missed responses (total average: 2.4%) was modulated by AGE, $\chi^2(6) = 20.42$, $p = .002$ (Figure 9a). Post hoc HSD comparisons revealed that the 51–60 and 71–86 yo participants missed more the target than the 61–70 yo (diff. = −2.81, 95% CI [−4.47, −1.14], log $OR = 0.07$, effect size: small; diff. = −2.76, [−4.39, 1.12], log $OR = 0.07$, effect size: small, respectively).

Thus, the missed response rate is greater in participants of 51–60 and 71–86 years of age.

Figure 4
Reaction Time According to Age



Note. Mean reaction time as a function of the age range. Within each boxplot (Tukey method), the horizontal line represents the group median, the box delineates the area between the first and third quartiles (interquartile range), the vertical line represents the interval between quantiles 5 and 95 (i.e., the dispersion of 90% of the population); superimposed to each boxplot, the dots represent individual means. RT+ = reaction time. See the online article for the color version of the figure.
* $p < .05$. ** $p < .01$. *** $p < .001$.

Anticipated Responses

The rate of anticipated responses (total average: 2.6%) was modulated by AGE, $\chi^2(6) = 24.61$, $p < .001$ (Figure 9b). Post hoc HSD analysis showed that the 41–50 yo made less anticipated responses than the 21–25 yo (diff. = −1.79, 95% CI [−2.79, 0.79], log *OR* = 0.23, effect size: small), 26–30 yo (diff. = −1.72, [−2.77, 0.67], log *OR* = 0.21, effect size: small), and 31–40 yo (diff. = −1.95, [−2.98, −0.92], log *OR* = 0.13, effect size: small). We also observed a main effect of the DISTRACTOR on the anticipated responses rate, $\chi^2(1) = 264.80$, $p < .001$, indicating that participants anticipated the target much more in Dis1 compared to the NoDis condition (diff. = 3.39, 95% CI [2.98, 3.79], log *OR* = 29.51, effect size: large).

In summary, the anticipated response rate is larger in participants aged from 21 to 40 years. Furthermore, irrespective of age, more anticipated responses are observed in trials with early distractors.

Discussion

The present cross-sectional study provides simultaneous but distinct measures reflecting the evolution of distractibility from 21 to 86 years old (seven age ranges). Here, the term "distractibility" is used to designate the propensity to pay attention to irrelevant events, a general state which results from the efficacy of different cognitive components. The present behavioral study shows that different components of distractibility follow distinct trajectories from early to late adulthood: Voluntary orienting is stable from 21 to 86 years of age, sustained attention progressively decreases, the distraction effect increases between 26 and 86 years old, the facilitation arousal-related effect increases after 70 years old, and eventually, impulsivity is greater between 21 and 40 years old than in later adulthood.

Unsurprisingly, we observe a progressive slowdown in RT after 30 years old. Rather than a decrease in voluntary attention, this phenomenon has been explained by a general slowdown in mental processes (Cerella, 1985; Salthouse, 1996, 2017).

Voluntary attention orienting is not found affected by age, suggesting a preserved ability to orient attention toward relevant targets in elderly, in agreement with some previous studies (Greenwood et al., 1993; Iarocci et al., 2009; Olk & Kingstone, 2015), but not with other findings showing a decline with aging (Brodeur & Enns, 1997; see also Erel & Levy, 2016 for a review). Functional and structural brain imaging studies suggest that this stability in performance would be supported by compensatory neuroplasticity mechanisms (ElShafei et al., 2020; Goh & Park, 2009; Paitel & Nielson, 2021;

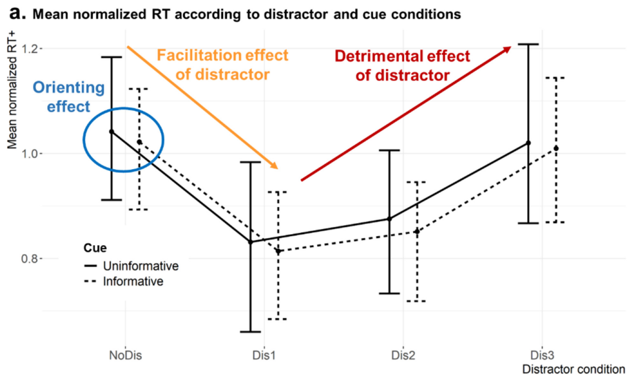
Table 5
Details for Post Hoc Analyses of RT_+

Age range *A*> or <*B*	Estimate (ms)	CI	*p*	*t*	ω^2	Effect size
21–25 < 41–50	−80.1	[−140.2, −20.0]	.002	3.9	0.64	Large
21–25 < 51–60	−89.8	[−151.2, −28.4]	<.001	4.3	0.69	Large
21–25 < 61–70	−117.4	[178.8, −56.0]	<.001	5.6	0.79	Large
21–25 < 71–86	−198.2	[−257.8, −138.7]	<.001	9.8	0.92	Large
26–30 < 41–50	−80.3	[−144.9, −15.8]	.005	3.6	0.60	Large
26–30 < 51–60	−90.0	[−155.7, −24.2]	.001	4.0	0.65	Large
26–30 < 61–70	−117.6	[−183.3, −51.9]	<.001	5.2	0.76	Large
26–30 < 71–86	−198.2	[−134.4, −262.4]	<.001	9.1	0.91	Large
31–40 < 51–60	−65.9	[−131.0, −0.8]	.045	2.9	0.48	Large
31–40 < 61–70	−93.5	[−158.6, −28.5]	<.001	4.2	0.68	Large
31–40 < 71–86	−174.4	[−237.6, −111.0]	<.001	8.1	0.89	Large
41–50 < 71–86	−118.1	[−180.2, −56.1]	<.001	5.6	0.79	Large
51–60 < 71–86	−108.5	[−171.8, −45.1]	<.001	5.0	0.75	Large
61–70 < 71–86	−80.8	[−144.1, −17.5]	.003	3.7	0.61	Large

Note. RT_+ = reaction times; CI = confidence interval.

Figure 5

Reaction Time According to Distractor and Cue Conditions



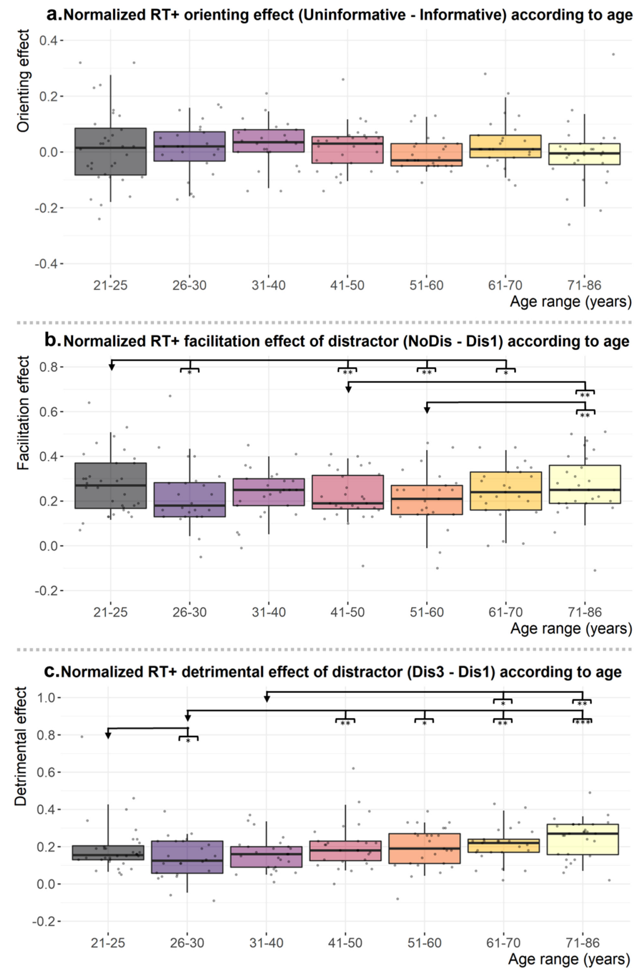
Note. Mean normalized reaction time as a function of the cue (informative or uninformative) and distractor (NoDis, Dis1, Dis2, and Dis3) conditions. The error bars represent the interval between quantiles 5 and 95 (i.e., the dispersion of 90% of the population). RT+ = reaction time; NoDis = no distractor condition; Dis = distractor condition. See the online article for the color version of the figure.

Reuter-Lorenz & Park, 2014). In addition, in line with studies showing a decline in sustained attention in older adults (Berardi et al., 2001; Davies & Davies, 1975; Fortenbaugh et al., 2015; Jackson & Balota, 2012; Parasuraman et al., 1989; Petton et al., 2019), we found that RT variability in no distractor trials particularly increases after 30 and 60 years old. This increase in performance variability with aging may be explained by a diminution in general (i.e., tonic) arousal (Dahl et al., 2022; T.-H. Lee et al., 2018), a reduction in nervous system integrity (MacDonald et al., 2009), and an increased variability in brain activation (Garrett et al., 2011) in the older age.

"Distraction," namely the detrimental effect of distractors upon behavioral performance, is increasing in elderly, in agreement with previous studies (Andrés et al., 2006; Berti et al., 2013; ElShafei et al., 2020; Leiva et al., 2014, 2016; Parmentier & Andrés, 2010). Importantly, the present study reveals that this heightened distraction develops gradually from early to late adulthood. Increased distraction effect after age 60 is assumed to ensue from greater brain processing of distractors, reduced recruitment of frontal-mediated inhibitory mechanisms, as well as prolonged reorientation toward the task (ElShafei et al., 2020, 2022; Horváth et al., 2009; Mager et al., 2005). In children, missed responses were found to be an interesting marker of sustained attention and distraction (Hoyer et al., 2021, 2023). The present study shows that RT is a more relevant marker to measure distraction in adults, while results indicating increased missed responses around 50 years of age are only related to small effect sizes. Interestingly, literature on distraction in elderly also reports that, on some memory tasks (Biss et al., 2013, 2018; Campbell et al., 2010; May & Hasher, 1998; Rowe et al., 2006; Thomas & Hasher, 2012), older adults normalize their performance or even outperform younger adults when past distractors later become relevant stimuli. Increased distraction with aging would help distractor encoding and storage in memory, facilitating its subsequent processing when relevant. Beyond cognitive decline, increased distraction from early to late adulthood may thus be an adaptive phenomenon aiming at boosting implicit learning.

Figure 6

Normalized Reaction Time Orienting, as Well as Facilitation and Detrimental Effects of Distractor According to Age



Note. (a) Normalized reaction time NoDis uninformative–NoDis informative orienting effect as a function of the age range. (b) Normalized reaction time NoDis–Dis1 facilitation effect as a function of the age range. (c) Normalized reaction time Dis3–Dis1 detrimental effect as a function of age range. Before calculating differences, RT_+ have been normalized as follows: participant's RT_+ single trial/participant's mean RT_+. Within each boxplot (Tukey method), the horizontal line represents the group median and the box delineates the area between the first and third quartiles (interquartile range); the vertical line represents the interval between quantiles 5 and 95 (i.e., the dispersion of 90% of the population); superimposed to each boxplot, the dots represent individual means. NoDis = no distractor condition; Dis = distractor condition; RT_+ = reaction times. See the online article for the color version of the figure.
* $p < .05$. ** $p < .01$. *** $p < .001$.

Distractors can also speed the response to a subsequent target (Andrés et al., 2006; Bidet-Caulet et al., 2015; Masson & Bidet-Caulet, 2019; Max et al., 2015; Näätänen, 1992; Wetzel et al., 2012). This facilitation effect has been proposed to result from a phasic increase in arousal (i.e., in alertness) mediated by the LC–NE

Table 6
Details for Significant Results of Planned Post Hoc Analyses of Normalized RT_+

Behavioral effect	Age range *A*> or <*B*	Estimate	CI	*p*	*t*	ω^2	Effect size
Facilitation effect of distractor NoDis–Dis1	21–25 > 26–30	0.049	[0.008, 0.089]	.018	2.4	0.19	Medium
	21–25 > 41–50	0.054	[0.016, 0.010]	.006	2.7	0.24	Medium
	21–25 > 51–60	0.066	[0.026, 0.106]	<.001	3.2	0.32	Medium
	41–50 < 71–86	−0.047	[−0.087, 0.006]	.024	−2.6	0.22	Medium
	51–60 < 71–86	−0.058	[−0.100, −0.016]	.006	−2.7	0.24	Medium
Detrimental effect of distractor Dis3–Dis1	21–25 > 26–30	0.087	[−0.008, 0.106]	.023	2.3	0.18	Medium
	26–30 < 41–50	−0.067	[−0.119, −0.016]	.010	−2.6	0.22	Medium
	26–30 < 51–60	−0.058	[−0.111, −0.006]	.030	−2.2	0.16	Medium
	26–30 < 61–70	−0.075	[−0.127, −0.024]	.004	−2.9	0.27	Large
	26–30 < 71–86	−0.104	[−0.154, −0.052]	<.001	−4.0	0.43	Large
	31–40 < 61–70	−0.054	[−0.105, −0.002]	.040	−2.0	0.13	Medium
	31–40 < 71–86	−0.082	[−0.133, −0.031]	.002	−3.2	0.32	Large

Note. RT_+ = reaction times; CI = confidence interval; NoDis = no distractor condition; Dis = distractor condition.

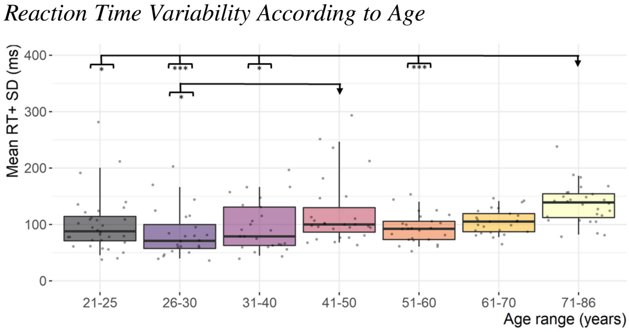
system (Aston-Jones & Cohen, 2005). Here, the facilitation effect is greater in participants of 21–25 and 71–86 years of age. The greater facilitation effect in the youngest adults is difficult to interpret since this effect is quite stable from 13 to 25 years old (Hoyer et al, 2021), and no changes in the LC–NE functioning have been observed in early adulthood (Liu et al., 2019). The facilitation effect seems to start increasing after 60 years of age: This may reflect an enhancement in phasic arousal, acting as a compensatory mechanism established in late adulthood to alleviate the deleterious impact of tonic arousal decrease with aging (Dahl et al., 2022; T.-H. Lee et al., 2018). Previous studies have found that the facilitation effect of distractor was not modulated by age (Andrés et al., 2006; ElShafei et al., 2020; Parmentier & Andrés, 2010), but they only compared younger and older adults from wide age ranges (18–29 and 50–83 years old). This highlights the importance of studying narrower age bands to capture the subtle changes in attention that occur with aging.

In the present study, impulsivity is assessed using different behavioral measures provided by the CAT (cue, random, distractor, and anticipated responses). Among these measures, only the proportion of anticipated responses changes with age: adults aged 21–40 are more likely to impulsively press the button before the target than their older peers, suggesting that motor inhibition is improving after 40 years old, in contradiction with previous studies showing increasing (Coyne et al., 1978; Maylor et al., 2011; Nielson et al., 2002) or stable (Hong et al., 2014; Hsieh et al., 2016; Lin & Cheng, 2020; Paitel & Nielson, 2021) impulsivity with aging. However, the present result should be taken cautiously as the size of this effect is small.

In line with both the frontal aging (Greenwood, 2000; West, 1996) and the inhibitory deficit (Hasher & Zacks, 1988) theories, this study shows that increased distractibility with aging originates from both reduced sustained attention and increased distraction. The frontal lobes decline with age has been related to weakened sustained attention abilities (Vallesi et al., 2021). Enhanced distraction can stem from an inhibitory deficit: reducing distractor processing in the brain would become less efficient with age (ElShafei et al., 2020, 2022). Our findings suggest that both reduction in sustained attention and enhancement in distraction start around 40 years old.

Most of the present findings are aligned with the prominent theories on the aging brain, whereby cognitive processes supported by frontal functions decline with age. Voluntary attention orienting, however, seems preserved with aging despite the fact that it relies on frontal lobe integrity (e.g., Bidet-Caulet et al., 2015). One explanation is the development of compensatory mechanisms. Stronger engagement of motor regions and reduced inhibition of irrelevant brain areas have been observed during target expectancy in participants aged 61–75 while performing the CAT (ElShafei et al., 2020, 2022). The compensation of lower attention efficiency by higher motor preparation in elderly might result in preserved voluntary attention-orienting performance. One may have expected that larger activation of motor preparation processes before target occurrence would lead to more anticipated responses in elderly, but the opposite trend was observed in this study: After 40 years of age, anticipated responses progressively fade. This reduction in impulsivity may actually be related to the general slowdown in response times which has been consistently observed in older adults, and is likely to ensue from the age-related decline of the central and peripheral motor systems (see Seidler et al., 2010 for a review) and a decrease in tonic arousal (Dahl et al., 2022; T.-H.

Figure 7
Reaction Time Variability According to Age



Note. RT_{+SD} averaged across blocks as a function of the age range. Within each boxplot (Tukey method), the horizontal line represents the group median, and the box delineates the area between the first and third quartiles (interquartile range); the vertical line represents the interval between quantiles 5 and 95 (i.e., the dispersion of 90% of the population); superimposed to each boxplot, the dots represent individual means. RT_{+SD} = standard deviation of reaction times. See the online article for the color version of the figure.
* $p < .05$. *** $p < .001$.

Table 7
Details for Significant Results of Post Hoc Analyses of RT_{+SD}

Age range $A>$ or $<B$	Estimate (ms)	CI	p	t	ω^2	Effect size
21–25 < 71–90	−36.0	[−68.9, −3.1]	.022	3.3	0.55	Large
26–30 < 41–50	−38.0	[−73.7, −2.4]	.028	3.2	0.54	Large
26–30 < 71–86	−52.8	[−88.1, −17.4]	<.001	4.7	0.71	Large
31–40 < 71–86	−40.4	[−75.4, −5.4]	.013	3.4	0.57	Large
51–60 < 71–86	−42.6	[−77.6, −7.6]	.005	3.6	0.60	Large

Note. RT_{+SD} = standard deviation of reaction times; CI = confidence interval.
* $p < .05$. ** $p < .01$. *** $p < .001$.

Lee et al., 2018). The heightening of phasic arousal after 60 years of age may be a compensatory mechanism to alleviate the diminishing efficiency of its tonic counterpart (Dahl et al., 2022), but could also compensate for the behavioral cost related to increased distraction (Gallant et al., 2020).

Compensatory strategies are at the heart of the scaffolding theory of aging and cognition. This theory assumes that two kinds of brain plasticity occur throughout aging: a negative (leading to cognitive decline) and a positive (supporting compensatory mechanisms) one (Goh & Park, 2009; Reuter-Lorenz & Park, 2014). Compensatory mechanisms can be established during aging to cope with enhanced distractibility. Motor preparation might compensate for reduced voluntary attention abilities such as orienting but would not be sufficient to compensate for the decline of processes requiring more cognitive resources, such as sustained attention. Enhanced distraction may also be compensatory. It reflects increased brain processing of irrelevant information with aging, which could boost implicit learning of irrelevant information and compensate for voluntary attention decline. In late adulthood, the larger increase in phasic arousal might compensate for enhanced distraction and lower tonic arousal.

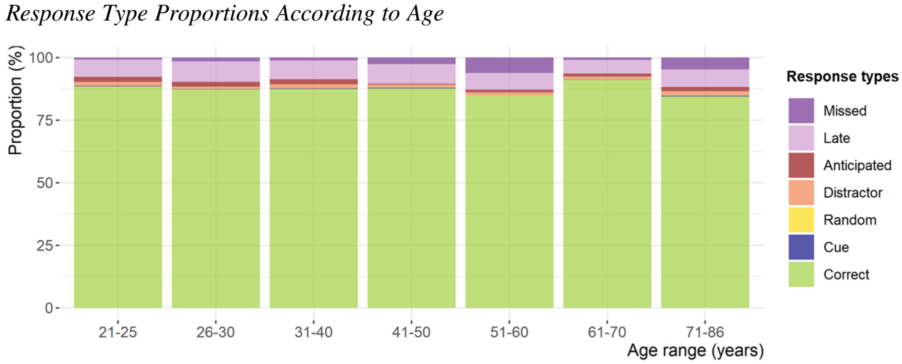
Beyond demonstrating that attention components follow distinct evolutive trajectories through early, middle, and late adulthood, the present findings highlight that aging affects attention processes dynamically: When a cognitive function declines, others adapt to compensate for its dimming. These dynamic trajectories may explain discrepancies in the literature: When age groups are compared, narrow instead of wide age ranges should be considered to precisely determine how aging shapes attention performance at every stage of adulthood.

Dissociating typical from pathological attention functioning during aging is a current challenge in clinical settings. For example, attention deficit would be a risk or a prodrome of Alzheimer's or Parkinson's disease (Becker et al., 2022; Cammisuli et al., 2021; Zhang et al., 2022). Detecting early and subtle abnormal attention changes during aging could thus contribute to estimate the risk of developing neurodegenerative disease (Becker et al., 2022) and might also help to define the evolutionary stage of the disease (Del Tredici & Braak, 2020). We are now working to determine whether the CAT is a reliable and sensitive measure for dissociating subclinical and clinical attention difficulties.

Constraints on Generality

This study has a number of strengths: large samples representative of the western general population, numerous age groups, use of a test providing multiple behavioral indices, and advanced statistical analyses. It also has some shortcomings: cross-sectional methodology, no physiological measurement provided for the facilitation effect of distractor, scarcity of some responses, lack of brain, and standardized neuropsychological measures. Specific question thus still needs to be addressed to capture a more comprehensive view of the brain and behavioral evolution of distractibility along aging. For example, an important next step will be to evaluate the influence of the circadian circle and tonic arousal on distractibility and to compare the evolutive trajectories of auditory and visual distraction with aging.

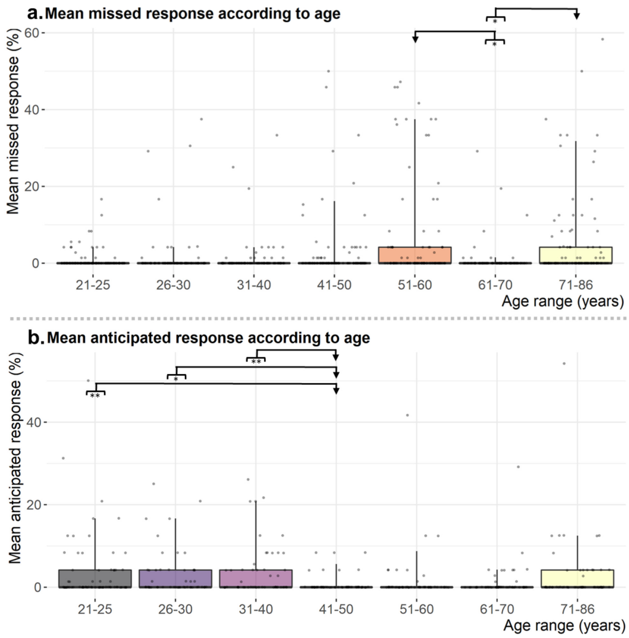
Figure 8
Response Type Proportions According to Age



Note. See the online article for the color version of the figure.

Figure 9

Missed and Anticipated Response Proportions According to Age



Note. (a) Missed responses percentage as a function of the age range. (b) Anticipated responses percentage (NoDis and Dis1) as function of the age range. Within each boxplot (Tukey method), the horizontal line represents the group median, the box delineates the area between the first and third quartiles (interquartile range); the vertical line represents the interval between quantiles 5 and 90 (i.e., the dispersion of 95% of the population); superimposed to each boxplot, the dots represent individual means. NoDis = no distractor condition; Dis = distractor condition. See the online article for the color version of the figure.
$^* p < .05$. $^{**} p < .01$.

Conclusions

Altogether, the present and past results from CAT studies in large samples of children and young adults (4–25 years old: Hoyer et al., 2021, 2023) suggest that: (a) Voluntary orienting is stable from 4 to 86 years old; (b) sustained attention develops from 4 to 5 years old, then from 8 to 12 years old, and declines after 30 years of age; (c) distraction is larger before 8 years old, is stable until 26 years of age, and then progressively increases along with adulthood; (d) arousal decreases between 9 and 13 years old and rebounds after 60 years old; and (e) impulsivity decreases between 11 and 40 years old.

By shedding light on the nonlinear evolving characteristics of distractibility components from early to late adulthood, the present findings further emphasize the relevance of using several restrained age ranges in cross-sectional studies of aging. They also provide useful information to better dissociate subclinical and pathological attention difficulties.

Context

Distractibility relies on different cognitive components, whose evolution with aging has, so far, remained poorly understood. In a large sample of participants ($N = 423$), we previously used the CAT to delineate the developmental trajectories of several distractibility components from childhood to early adulthood (Hoyer et al., 2021, 2023). The present study sheds light on the simultaneous, but distinct, trajectories taken by the distractibility components from early to late adulthood ($N = 191$). Attention-deficit/hyperactivity disorder in older adults (Michielsen et al., 2012) is often misdiagnosed and can even be mistaken with dementia (Callahan et al., 2022; Sasaki et al., 2022). Thus, the present findings could help to dissociate subclinical and pathological attention difficulties in medical settings. With this in mind, we are currently performing studies to show the content and criterion validity of the CAT to further enable its use in clinical settings.

Preliminary data from this study have been presented during lab meetings only. The final data have not been presented at national or international conferences.

References

Amer, T., Anderson, J. A. E., Campbell, K. L., Hasher, L., & Grady, C. L. (2016). Age differences in the neural correlates of distraction regulation: A network interaction approach. *NeuroImage*, *139*, 231–239. https://doi.org/10.1016/j.neuroimage.2016.06.036

Andrés, P., Parmentier, F. B. R., & Escera, C. (2006). The effect of age on involuntary capture of attention by irrelevant sounds: A test of the frontal hypothesis of aging. *Neuropsychologia*, *44*(12), 2564–2568. https://doi.org/10.1016/j.neuropsychologia.2006.05.005

Aston-Jones, G., & Cohen, J. D. (2005). An integrative theory of locus coeruleus-norepinephrine function: Adaptive gain and optimal performance. *Annual Review of Neuroscience*, *28*(1), 403–450. https://doi.org/10.1146/annurev.neuro.28.061604.135709

Barratt, E. S., & Patton, J. H. (1983). Impulsivity: Cognitive, behavioral, and psychophysiological correlates. In M. Zuckerman (Ed.), *Biological bases of sensation seeking, impulsivity and anxiety* (pp. 77–122). Lawrence Erlbaum Associates.

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Becker, S., Sharma, M. J., & Callahan, B. L. (2022). ADHD and neurodegenerative disease risk: A critical examination of the evidence. *Frontiers in Aging Neuroscience*, *13*, Article 826213. https://doi.org/10.3389/fnagi.2021.826213

Ben-Shachar, M. S., Lüdecke, D., & Makowski, D. (2020). effectsize: Estimation of effect size indices and standardized parameters. *Journal of Open Source Software*, *5*(56), Article 2815. https://doi.org/10.21105/joss.02815

Berardi, A., Parasuraman, R., & Haxby, J. V. (2001). Overall vigilance and sustained attention decrements in healthy aging. *Experimental Aging Research*, *27*(1), 19–39. https://doi.org/10.1080/03610730126014

Berti, S., Grunwald, M., & Schröger, E. (2013). Age dependent changes of distractibility and reorienting of attention revisited: An event-related potential study. *Brain Research*, *1491*, 156–166. https://doi.org/10.1016/j.brainres.2012.11.009

Bidet-Caulet, A., Bottemanne, L., Fonteneau, C., Giard, M.-H., & Bertrand, O. (2015). Brain dynamics of distractibility: Interaction between top-down and bottom-up mechanisms of auditory attention. *Brain Topography*, *28*(3), 423–436. https://doi.org/10.1007/s10548-014-0354-x

Biss, R., Ngo, J., Hasher, L., Campbell, K., & Rowe, G. (2013). Distraction can reduce age-related forgetting. *Psychological Science*, *24*(4), 448–455. https://doi.org/10.1177/0956797612457386

Biss, R., Rowe, G., Weeks, J., Hasher, L., & Murphy, K. (2018). Leveraging older adults' susceptibility to distraction to improve memory for face-name associations. *Psychology and Aging*, *33*(1), 158–164. https://doi.org/10.1037/pag0000192

Brodeur, D. A., & Enns, J. T. (1997). Covert visual orienting across the life-span. *Canadian Journal of Experimental Psychology*, *51*(1), 20–35. https://doi.org/10.1037/1196-1961.51.1.20

Callahan, B. L., Ramakrishnan, N., Shammi, P., Bierstone, D., Taylor, R., Ozzoude, M., Goubran, M., Stuss, D. T., & Black, S. E. (2022). Cognitive and neuroimaging profiles of older adults with attention deficit/hyperactivity disorder presenting to a memory clinic. *Journal of Attention Disorders*, *26*(8), 1118–1129. https://doi.org/10.1177/10870547211060546

Cammisuli, D. M., Pagni, C., Palermo, G., Frosini, D., Bonaccorsi, J., Radicchi, C., Cintoli, S., Tommasini, L., Tognoni, G., Ceravolo, R., & Bonuccelli, U. (2021). Mild cognitive impairment in de novo Parkinson's disease: Selective attention deficit as early sign of neurocognitive decay. *Frontiers in Psychology*, *12*, Article 546476. https://doi.org/10.3389/fpsyg.2021.546476

Campbell, K. L., Hasher, L., & Thomas, R. C. (2010). Hyper-binding: A unique age effect. *Psychological Science*, *21*(3), 399–405. https://doi.org/10.1177/0956797609359910

Cerella, J. (1985). Information processing rates in the elderly. *Psychological Bulletin*, *98*(1), 67–83. https://doi.org/10.1037/0033-2909.98.1.67

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Routledge. https://doi.org/10.4324/9780203771587

Cohen, J. (1992). A power primer. *Psychological Bulletin*, *112*(1), 155–159. https://doi.org/10.1037//0033-2909.112.1.155

Colcombe, S. J., Kramer, A. F., Erickson, K. I., & Scalf, P. (2005). The implications of cortical recruitment and brain morphology for individual differences in inhibitory function in aging humans. *Psychology and Aging*, *20*(3), 363–375. https://doi.org/10.1037/0882-7974.20.3.363

Coyne, A. C., Whitbourne, S. K., & Glenwick, D. S. (1978). Adult age differences in reflection-impulsivity. *Journal of Gerontology*, *33*(3), 402–407. https://doi.org/10.1093/geronj/33.3.402

Dahl, M. J., Mather, M., & Werkle-Bergner, M. (2022). Noradrenergic modulation of rhythmic neural activity shapes selective attention. *Trends in Cognitive Sciences*, *26*(1), 38–52. https://doi.org/10.1016/j.tics.2021.10.009

Davies, A. D. M., & Davies, D. B. (1975). The effects of noise and time of day upon age differences in performance at two checking tasks. *Ergonomics*, *18*(3), 321–336. https://doi.org/10.1080/00140137508931465

Del Tredici, K., & Braak, H. (2020). To stage, or not to stage. *Current Opinion in Neurobiology*, *61*, 10–22. https://doi.org/10.1016/j.conb.2019.11.008

ElShafei, H. A., Fornoni, L., Masson, R., Bertrand, O., & Bidet-Caulet, A. (2020). Age-related modulations of alpha and gamma brain activities underlying anticipation and distraction. *PLoS One*, *15*(3), Article e0229334. https://doi.org/10.1371/journal.pone.0229334

ElShafei, H. A., Masson, R., Fakche, C., Fornoni, L., Moulin, A., Caclin, A., & Bidet-Caulet, A. (2022). Age-related differences in bottom-up and top-down attention: Insights from EEG and MEG. *The European Journal of Neuroscience*, *55*(5), 1215–1231. https://doi.org/10.1111/ejn.15617

Erel, H., & Levy, D. A. (2016). Orienting of visual attention in aging. *Neuroscience and Biobehavioral Reviews*, *69*, 357–380. https://doi.org/10.1016/j.neubiorev.2016.08.010

Escera, C., Alho, K., Schröger, E., & Winkler, I. (2000). Involuntary attention and distractibility as evaluated with event-related brain potentials. *Audiology & Neuro-Otology*, *5*(3–4), 151–166. https://doi.org/10.1159/000013877

Fortenbaugh, F. C., DeGutis, J., Germine, L., Wilmer, J., Grosso, M., Russo, K., & Esterman, M. (2015). Sustained attention across the lifespan in a sample of 10,000: Dissociating ability and strategy. *Psychological Science*, *26*(9), 1497–1510. https://doi.org/10.1177/0956797615594896

Fox, J., & Weisberg, S. (2018). *An R companion to applied regression*. SAGE Publications.

Gallant, S. N., Durbin, K. A., & Mather, M. (2020). Age differences in vulnerability to distraction under arousal. *Psychology and Aging*, *35*(5), 780–791. https://doi.org/10.1037/pag0000426

Garrett, D. D., Kovacevic, N., McIntosh, A. R., & Grady, C. L. (2011). The importance of being variable. *The Journal of Neuroscience*, *31*(12), 4496–4503. https://doi.org/10.1523/JNEUROSCI.5641-10.2011

Goh, J. O., & Park, D. C. (2009). Neuroplasticity and cognitive aging: The scaffolding theory of aging and cognition. *Restorative Neurology and Neuroscience*, *27*(5), 391–403. https://doi.org/10.3233/RNN-2009-0493

Greenwood, P. M. (2000). The frontal aging hypothesis evaluated. *Journal of the International Neuropsychological Society*, *6*(6), 705–726. https://doi.org/10.1017/S1355617700666092

Greenwood, P. M., Parasuraman, R., & Haxby, J. V. (1993). Changes in visuospatial attention over the adult lifespan. *Neuropsychologia*, *31*(5), 471–485. https://doi.org/10.1016/0028-3932(93)90061-4

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. In G. H. Bower (Ed.), *Psychology of learning and motivation* (Vol. 22, pp. 193–225). Academic Press. https://doi.org/10.1016/S0079-7421(08)60041-9

Healey, M. K., Campbell, K. L., & Hasher, L. (2008). Cognitive aging and increased distractibility: Costs and potential benefits. *Progress in Brain Research*, *169*, 353–363. https://doi.org/10.1016/S0079-6123(07)00022-2

Hong, X., Sun, J., Bengson, J. J., & Tong, S. (2014). Age-related spatiotemporal reorganization during response inhibition. *International Journal of Psychophysiology*, *93*(3), 371–380. https://doi.org/10.1016/j.ijpsycho.2014.05.013

Horváth, J., Czigler, I., Birkás, E., Winkler, I., & Gervai, J. (2009). Age-related differences in distraction and reorientation in an auditory task. *Neurobiology of Aging*, *30*(7), 1157–1172. https://doi.org/10.1016/j.neurobiolaging.2007.10.003

Hoyer, R. S., Elshafei, H., Hemmerlin, J., Bouet, R., & Bidet-Caulet, A. (2021). Why are children so distractible? Development of attention and motor control from childhood to adulthood. *Child Development*, *92*(4), e716–e737. https://doi.org/10.1111/cdev.13561

Hoyer, R. S., Pakulak, E., Bidet-Caulet, A., & Karns, C. M. (2023). Relationships among age, socioeconomic status, and distractibility in preschoolers as assessed by the competitive attention test. *Journal of Experimental Child Psychology*, *227*, Article 105584. https://doi.org/10.1016/j.jecp.2022.105584

Hsieh, S., Wu, M., & Tang, C.-H. (2016). Adaptive strategies for the elderly in inhibiting irrelevant and conflict no-go trials while performing the go/no-go task. *Frontiers in Aging Neuroscience*, *7*, Article 243. https://doi.org/10.3389/fnagi.2015.00243

Iarocci, G., Enns, J. T., Randolph, B., & Burack, J. A. (2009). The modulation of visual orienting reflexes across the lifespan. *Developmental Science*, *12*(5), 715–724. https://doi.org/10.1111/j.1467-7687.2009.00810.x

Jackson, J. D., & Balota, D. A. (2012). Mind-wandering in younger and older adults: Converging evidence from the sustained attention to response task and reading for comprehension. *Psychology and Aging*, *27*(1), 106–119. https://doi.org/10.1037/a0023933

JASP—A Fresh Way to Do Statistics. (2021). *JASP—Free and user-friendly statistical software*. Retrieved October 12, 2021, from https://jasp-stats.org/

Lee, M. D., & Wagenmakers, E.-J. (2013). *Bayesian cognitive modeling: A practical course*. Cambridge University Press. https://doi.org/10.1017/CBO9781139087759

Lee, T.-H., Greening, S. G., Ueno, T., Clewett, D., Ponzio, A., Sakaki, M., & Mather, M. (2018). Arousal increases neural gain via the locus coeruleus-norepinephrine system in younger adults but not in older adults. *Nature Human Behaviour*, *2*(5), 356–366. https://doi.org/10.1038/s41562-018-0344-1

Leiva, A., Andrés, P., & Parmentier, F. B. R. (2021). Aging increases cross-modal distraction by unexpected sounds: Controlling for response speed. *Frontiers in Aging Neuroscience*, *13*, Article 733388. https://doi.org/10.3389/fnagi.2021.733388

Leiva, A., Andrés, P., Servera, M., Verbruggen, F., & Parmentier, F. B. R. (2016). The role of age, working memory, and response inhibition in deviance distraction: A cross-sectional study. *Developmental Psychology*, *52*(9), 1381–1393. https://doi.org/10.1037/dev0000163

Leiva, A., Parmentier, F., & Andrés, P. (2014). Aging increases distraction by auditory oddballs in visual, but not auditory tasks. *Psychological Research*, *79*(3), 401–410. https://doi.org/10.1007/s00426-014-0573-5

Lin, M.-Y., & Cheng, C.-H. (2020). Effect of age in auditory go/no-go tasks: A magnetoencephalographic study. *Brain Sciences*, *10*(10), Article 667. https://doi.org/10.3390/brainsci10100667

Liu, K. Y., Acosta-Cabronero, J., Cardenas-Blanco, A., Loane, C., Berry, A. J., Betts, M. J., Kievit, R. A., Henson, R. N., Düzel, E., Howard, R., & Hämmerer, D. (2019). In vivo visualization of age-related differences in the locus coeruleus. *Neurobiology of Aging*, *74*, 101–111. https://doi.org/10.1016/j.neurobiolaging.2018.10.014

MacDonald, S. W. S., Li, S.-C., & Bäckman, L. (2009). Neural underpinnings of within-person variability in cognitive functioning. *Psychology and Aging*, *24*(4), 792–808. https://doi.org/10.1037/a0017798

Mager, R., Falkenstein, M., Störmer, R., Brand, S., Müller-Spahn, F., & Bullinger, A. H. (2005). Auditory distraction in young and middle-aged adults: A behavioural and event-related potential study. *Journal of Neural Transmission*, *112*(9), 1165–1176. https://doi.org/10.1007/s00702-004-0258-0

Masson, R., & Bidet-Caulet, A. (2019). Fronto-central P3a to distracting sounds: An index of their arousing properties. *NeuroImage*, *185*, 164–180. https://doi.org/10.1016/j.neuroimage.2018.10.041

Max, C., Widmann, A., Kotz, S. A., Schröger, E., & Wetzel, N. (2015). Distraction by emotional sounds: Disentangling arousal benefits and orienting costs. *Emotion*, *15*(4), 428–437. https://doi.org/10.1037/a0039041

May, C. P., & Hasher, L. (1998). Synchrony effects in inhibitory control over thought and action. *Journal of Experimental Psychology: Human Perception and Performance*, *24*(2), 363–379. https://doi.org/10.1037//0096-1523.24.2.363

Maylor, E. A., Birak, K. S., & Schlaghecken, F. (2011). Inhibitory motor control in old age: Evidence for de-automatization? *Frontiers in Psychology*, *2*, Article 132. https://doi.org/10.3389/fpsyg.2011.00132

Michielsen, M., Semeijn, E., Comijs, H. C., van de Ven, P., Beekman, A. T. F., Deeg, D. J. H., & Kooij, J. J. S. (2012). Prevalence of attention-deficit hyperactivity disorder in older adults in the Netherlands. *The British Journal of Psychiatry*, *201*(4), 298–305. https://doi.org/10.1192/bjp.bp.111.101196

Näätänen, R. (1992). *Attention and brain function*. Lawrence Erlbaum Associates.

Nielson, K. A., Langenecker, S. A., & Garavan, H. (2002). Differences in the functional neuroanatomy of inhibitory control across the adult life span. *Psychology and Aging*, *17*(1), 56–71. https://doi.org/10.1037//0882-7974.17.1.56

Olk, B., & Kingstone, A. (2015). Attention and ageing: Measuring effects of involuntary and voluntary orienting in isolation and in combination. *British Journal of Psychology*, *106*(2), 235–252. https://doi.org/10.1111/bjop.12082

Paitel, E., & Nielson, K. (2021). Temporal dynamics of event-related potentials during inhibitory control characterize age-related neural compensation. *Symmetry*, *13*(12), Article 2323. https://doi.org/10.3390/sym13122323

Parasuraman, R., Nestor, P. G., & Greenwood, P. (1989). Sustained-attention capacity in young and older adults. *Psychology and Aging*, *4*(3), 339–345. https://doi.org/10.1037/0882-7974.4.3.339

Parmentier, F. B. R., & Andrés, P. (2010). The involuntary capture of attention by sound: Novelty and postnovelty distraction in young and older adults. *Experimental Psychology*, *57*(1), 68–76. https://doi.org/10.1027/1618-3169/a000009

Petersen, S. E., & Posner, M. I. (2012). The attention system of the human brain: 20 years after. *Annual Review of Neuroscience*, *35*(1), 73–89. https://doi.org/10.1146/annurev-neuro-062111-150525

Petton, M., Perrone-Bertolotti, M., Mac-Auliffe, D., Bertrand, O., Aguera, P.-E., Sipp, F., Batthacharjee, M., Isnard, J., Minotti, L., Rheims, S., Kahane, P., Herbillon, V., & Lachaux, J.-P. (2019). BLAST: A short computerized test to measure the ability to stay on task. Normative behavioral data and detailed cortical dynamics. *Neuropsychologia*, *134*, Article 107151. https://doi.org/10.1016/j.neuropsychologia.2019.107151

Posner, M. I., Cohen, Y., & Rafal, R. D. (1982). Neural systems control of spatial orienting. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *298*(1089), 187–198. https://doi.org/10.1098/rstb.1982.0081

Reuter-Lorenz, P. A., & Park, D. C. (2014). How does it STAC up? Revisiting the scaffolding theory of aging and cognition. *Neuropsychology Review*, *24*(3), 355–370. https://doi.org/10.1007/s11065-014-9270-9

Rey-Mermet, A., & Gade, M. (2018). Inhibition in aging: What is preserved? What declines? A meta-analysis. *Psychonomic Bulletin & Review*, *25*(5), 1695–1716. https://doi.org/10.3758/s13423-017-1384-7

Rowe, G., Valderrama, S., Hasher, L., & Lenartowicz, A. (2006). Attentional disregulation: A benefit for implicit memory. *Psychology and Aging*, *21*(4), 826–830. https://doi.org/10.1037/0882-7974.21.4.826

Ruan, Q., Yu, Z., Chen, M., Bao, Z., Li, J., & He, W. (2015). Cognitive frailty, a novel target for the prevention of elderly dependency. *Ageing Research Reviews*, *20*, 1–10. https://doi.org/10.1016/j.arr.2014.12.004

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review*, *103*(3), 403–428. https://doi.org/10.1037/0033-295x.103.3.403

Salthouse, T. A. (2017). Neural correlates of age-related slowing. In *Cognitive neuroscience of aging: Linking cognitive and cerebral aging* (2nd ed., pp. 259–272). Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199372935.003.0011

Sasaki, H., Jono, T., Fukuhara, R., Honda, K., Ishikawa, T., Boku, S., & Takebayashi, M. (2022). Late-manifestation of attention-deficit/hyperactivity disorder in older adults: An observational study. *BMC Psychiatry*, *22*(1), Article 354. https://doi.org/10.1186/s12888-022-03978-0

Seidler, R. D., Bernard, J. A., Burutolu, T. B., Fling, B. W., Gordon, M. T., Gwin, J. T., Kwak, Y., & Lipps, D. B. (2010). Motor control and aging: Links to age-related brain structural, functional, and biochemical effects. *Neuroscience and Biobehavioral Reviews*, *34*(5), 721–733. https://doi.org/10.1016/j.neubiorev.2009.10.005

Tamnes, C. K., Østby, Y., Fjell, A. M., Westlye, L. T., Due-Tønnessen, P., & Walhovd, K. B. (2010). Brain maturation in adolescence and young adulthood: Regional age-related changes in cortical thickness and white matter volume and microstructure. *Cerebral Cortex*, *20*(3), 534–548. https://doi.org/10.1093/cercor/bhp118

Thomas, R. C., & Hasher, L. (2012). Reflections of distraction in memory: Transfer of previous distraction improves recall in younger and older adults. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *38*(1), 30–39. https://doi.org/10.1037/a0024882

Vallesi, A., Tronelli, V., Lomi, F., & Pezzetta, R. (2021). Age differences in sustained attention tasks: A meta-analysis. *Psychonomic Bulletin & Review*, *28*(6), 1755–1775. https://doi.org/10.3758/s13423-021-01908-x

West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin*, *120*(2), 272–292. https://doi.org/10.1037/0033-2909.120.2.272

Wetzel, N., Buttelmann, D., Schieler, A., & Widmann, A. (2016). Infant and adult pupil dilation in response to unexpected sounds. *Developmental Psychobiology*, *58*(3), 382–392. https://doi.org/10.1002/dev.21377

Wetzel, N., & Schröger, E. (2014). On the development of auditory distraction: A review: Development of auditory distraction. *PsyCh Journal*, *3*(1), 72–91. https://doi.org/10.1002/pchj.49

Wetzel, N., Widmann, A., & Schröger, E. (2012). Distraction and facilitation-two faces of the same coin? *Journal of Experimental Psychology: Human Perception and Performance*, *38*(3), 664–674. https://doi.org/10.1037/a0025856

Yeatman, J. D., Wandell, B. A., & Mezer, A. A. (2014). Lifespan maturation and degeneration of human brain white matter. *Nature Communications*, *5*(1), Article 1. https://doi.org/10.1038/ncomms5932

Zhang, L., Du Rietz, E., Kuja-Halkola, R., Dobrosavljevic, M., Johnell, K., Pedersen, N. L., Larsson, H., & Chang, Z. (2022). Attention-deficit/hyperactivity disorder and Alzheimer's disease and any dementia: A multi-generation cohort study in Sweden. *Alzheimer's & Dementia*, *18*(6), 1155–1163. https://doi.org/10.1002/alz.12462

Received August 26, 2022
Revision received May 31, 2023
Accepted June 9, 2023 ■