Age-dependent attentional style and pupil-linked arousal regulate the reportability of spontaneous mental states

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Abstract

The reportability of spontaneous thinking relies significantly on attention and arousal. As these cognitive faculties change with age, we aimed at testing how spontaneous mental state reportability is influenced accordingly. Using experience sampling, 20 senior (65-75yrs) and 20 young participants (20-30yrs) were prompted to report mind-wandering (MW), mind-blanking (MB), or sensory-related (S) mental states at random times. Attention was assessed with the Attentional Style Questionnaire, and arousal with continuous monitoring of pupil diameter. First, we found more MW occurrences than MB or S across all participants. For young responders, we replicated that MW was more prevalent in easily-distracted participants. In seniors, though, MW was more prevalent in participants with a higher focused attentional style. In senior participants who reported being more easily distracted, MW was associated with lower arousal (pupil constriction) and MB with higher arousal (pupil dilation), reversing the pattern found for young adults and focused seniors. We propose that these effects may result from intentional MW, during which senior participants allocate attentional resources to mentally engage inwards, as opposed to younger participants who get more easily distracted by their own mental activity leading to unintentional MW. Together, our results highlight age-dependent mechanisms by which attentional style and pupil-linked arousal regulate the reportability of spontaneous mental states across age.

Introduction

Spontaneous thinking refers to our ability to entertain and transition among various mental states (Christoff et al., 2016). Our mental states can be described in terms of content and the relation we bear with this content. Indicative examples are task-related and task-unrelated thoughts, mind-wandering, daydreaming, thoughts about our environment while remembering, imagining or perceiving a scene. The way we transition among mental states can be deliberate or automatic, which is heavily based on how we allocate our attentional resources for cognitive control. For example, we can choose to focus on reading a difficult text by holding our thoughts back when distracted. Or we find it hard to read once our attention is captured by a buzzing noise in a quiet environment (Christoff et al., 2016).

Attention can also get attracted by thoughts taking the form of mind-wandering (MW) (Schooler et al., 2011). MW is a mental state which consists in diverting attention from mental content which is related to a task to unrelated inner thoughts, fantasies, feelings, and other musings (Smallwood & Schooler, 2006). This can happen when attention disengages from perception (Schooler et al., 2011) to the point that the propensity to MW could be predicted by individual differences in sustained attention ability (Walker & Trick, 2018). There can be moments, though, during which we fail to report a mental content, feeling like the mind is absent or "blanked" (Kawagoe et al., 2019; Ward & Wegner, 2013). Mind blanking (MB) has been defined as "reports of reduced awareness and a temporary absence of thought (empty mind) or lack of memory for immediately past thoughts [which] can be considered as the phenomenological dimension of a distinct kind of attentional lapse" (Andrillon et al., 2019, p2). Such attentional lapses linked to MB were later shown to correlate with the presence of transient slow wave activity indicative of low cortical arousal even during wakefulness (Andrillon et al., 2021). Together, the mental states of MW and MB indicate that attention and physiological arousal are crucial factors that mediate their reportability. What remains to be shown is whether and how attention and arousal can jointly influence the reportability of spontaneous mental states.

We here aimed at addressing this question by evaluating mental state reportability in healthy ageing, by considering this cohort as an appropriate proxy to attentional and arousal modifications. Age-related selective attention changes, for example, have been evidenced by increments in target identification time and error rate (Plude & Hoyer, 1986). Differences in divided attention (Wright, 1981) also manifested in simple immediate attention span, selectivity, capacity to inhibit interference of non-pertinent signals, and attentive shifting (Commodari & Guarnera, 2008). Additionally, aging affects vigilance in sustained attention tasks (Berardi et al., 2001) and arousal as revealed by decreased pupil size (Birren et al., 1950). Therefore, both attentional resources and arousal changes are concomitant in senior individuals and were shown to influence task performance (Craik & Salthouse, 2008). However, the impact of age-dependent changes in attentional resources and arousal on spontaneous thinking remains unknown.

By comparing healthy seniors to a group of healthy young participants, we aim to characterize the profile of mental state reportability for each group. We hypothesize that seniors in particular will:

1) report fewer MW events (Gyurkovics et al., 2018; Jackson & Balota, 2012; Seli et al., 2017) due to a more focused attentional style, in line with previous findings that senior adults have higher task focus than younger individuals (Maillet et al., 2020; Seli et al., 2021),

2) report more incidences of MB reports, due to lower arousal levels as monitored by pupillometry (Birren et al., 1950), and

3) show an interaction between attentional style and arousal, due to age-dependent changes in arousal and attentional abilities (Berardi, Raja Parasuraman, James V., 2001; Craik & Salthouse, 2008).

Methods

Participants. Forty-two French-speaking adults were recruited by means of advertisement in University of Liège and University of the Third Age. Participants were split in two groups: *seniors* (65-75yrs) and *young* participants (20-30yrs). One senior and one young participant were excluded due to technical problems with ocular recordings, resulting in a final cohort of 20 seniors (14 females, mean age=69.3±3.1) and 20 young participants (15 females, mean age=25.4±2.4). All individuals had normal or corrected-to-normal vision and audition with no history of psychiatric or neurological disorders. The study was approved by the ethics committee of the Faculty of Psychology, Speech Therapy and Educational Science of the University of Liège. All participants provided written informed consent prior to the study.

Procedure. Participants were invited to sit comfortably in a dimly lit room in front of a computer screen and a keyboard. They were instructed to use earphones (ER-3C, Etymotic Research) to ensure auditory isolation from external sounds and reduction of auditory distraction from potential surrounding sound sources. Participants wore oculometric glasses (Phasya Drowsimeter R100) which allowed for pupil size monitoring, which was considered as an objective physiological marker of arousal (Alnaes et al., 2014). Before the experiment, participants were asked to fixate a point on the screen for a few seconds to calibrate the eye recording system.

Participants were explained the aim of the task and were given the definitions of "Mind-Wandering" (MW), "Mind-Blanking" (MB), and "Sensations" (S). MW was defined as all types of thoughts, related or not to the present environment, such as "I think about the screen I am looking at" or "I am thinking about what I am going to eat tonight". MB was defined as "an empty mind", "thinking about nothing" but also "no memory of mental content". S was defined as the sensorial acknowledgment related to the five senses of one or more stimuli without any thought attached to it, such as "I heard someone's voice without thinking". The definitions were repeated until they were correctly distinguished and understood.

The experiment was designed and presented using the PsychoPy toolbox (PsychoPy3 v.2020.2.10). The task utilized the probe-caught experience-sampling method (Smallwood & Schooler, 2006) consisting of the participant instructed to maintain their gaze on the screen while their mind was allowed to go freely and 40 auditory prompts (1s tone-pip, 440 Hz frequency, played at 50 dB, sampled at 44000 Hz) presented at random time intervals, ranging between 30 to 60 sec. The prompts invited participants to report on their mental state as it was prior to the tone by using one out of three options: "MW", "MB", and "S" (Figure 1).

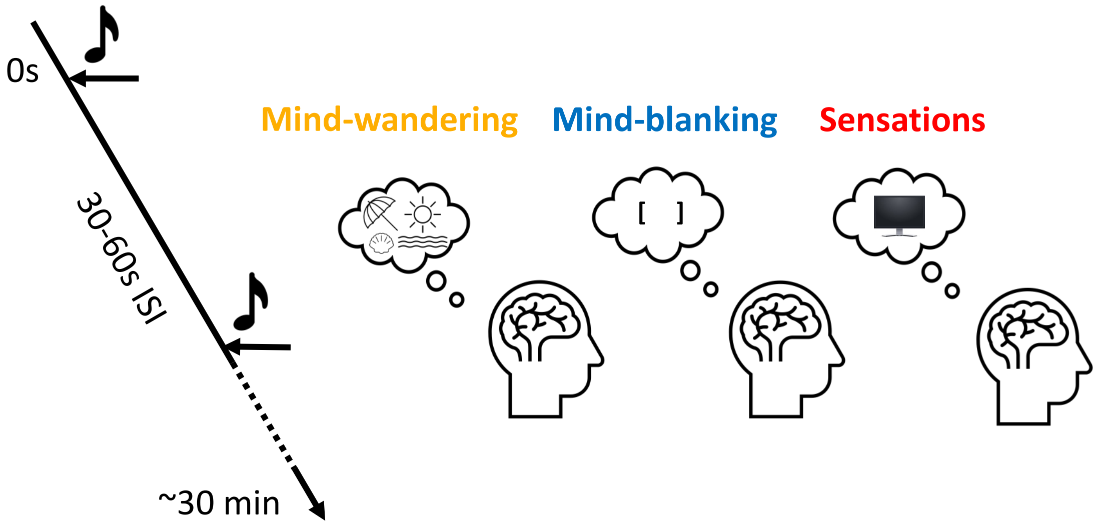

Figure 1. Experience-sampling task. Participants' ongoing resting state was interrupted by 40 auditory prompts randomly appearing with an inter-stimulus interval (ISI) 30 to 60 sec. The prompt invited them to report their mental state as it was beforehand by choosing among "Mind-Wandering", "Mind-Blanking", and "Sensations" (*e.g.,* the view of the experiment screen).

The experiment started upon the participant's keypress. The computer screen was maintained grey throughout the experiment except after the sound probes when the response options and their corresponding key press appeared on the screen. After the response was provided, the screen turned grey again. Participants were instructed to keep their gaze on the screen and their eyes open during the whole experiment. The total duration of the experiment was about 30 minutes.

Questionnaires. Upon task completion, participants were administered the Attentional Style Questionnaire (ASQ), the validated French version Generalized Anxiety Disorder – 7 (GAD-7), and the Mini Mental State Examination (MMSE, only for seniors).

The ASQ is a self-assessment questionnaire measuring the capacity of an individual to maintain attention on task-related stimuli and not to be distracted by interfering stimuli (Smallwood & Schooler, 2006). A lower ASQ score reflects a more focused attentional style. Only psychometrically validated items of the questionnaire were used (Kraft et al., 2020), forming 12 items ranked on a Likert scale ranging from "strongly disagree" to "strongly agree". We also considered anxiety symptoms as a potential confound of our results as they have been reported to affect attentional abilities, pupil size variations and the occurrence of spontaneous mental states (Makovac et al., 2019). Participants filled the GAD-7, a 7-item self-rated questionnaire designed to assess the intensity of anxiety symptoms (Spitzer et al., 2006). Each item is rated on a Likert scale from 0 (not at all) to 4 (nearly every day).

The Mini Mental State Examination (MMSE; Folstein et al., 1975) examined general cognitive functions and check the absence of any major neurocognitive disorder. The MMSE consists of 6 categories (orientation, learning, attention and calculation, reminder, language, and constructive praxis). Although the classification of the obtained score depends on the person's socio-cultural level, a score of 24 or less on a maximum of 30 indicates mild dementia.

Behavioral analysis. Collected behavioral data concerned mental state reports and reaction times. Mental state reportability was determined in terms of overall occurrence rate for each mental state (MW, MB, S), reaction times with regards to button presses, the distribution of appearance of mental state reports across the experiment, and inter-state transition dynamics.

To test whether mental state occurrence rate depended on the type of mental state, age group and attentional style of anxiety, we used a generalized linear-mixed model with a binomial distribution, the number of trials (n=40) as weighting factor and participants defined as random effect factors. The influence on reaction times of mental states, age group and attentional style or anxiety was assessed with a generalized linear mixed-effect model with a gamma distribution and an inverse link function, with participants defined as random effect factors. In both cases, the glmer function in R was used.

Post-hoc paired non-parametric Wilcoxon signed-rank tests with false discovery rate (FDR) correction for multiple comparisons were used to assess the difference in occurrence rates across mental states within groups. Non-parametric unpaired Wilcoxon rank-sum tests with FDR correction for multiple comparisons were used to assess the difference in the rates of occurrence of mental states, attentional style and anxiety between groups. Effect sizes were computed using the formula: $r = Z/\sqrt{n}$, where Z is the Z-value and n the number of participants (Pallant, 2020). The correlation between ASQ and GAD scores was assessed with Pearson's correlation coefficient (R).

Distribution of the mental states reportability across the entire experiment was statistically assessed by comparing it to a uniform distribution using Chi-squared test. Inter-state transition dynamics was assessed by computing the probability of transition between mental states for each participant and testing for differences across age groups using Wilcoxon-rank sum tests with FDR correction for multiple comparisons.

Physiological analysis. Collected physiological data concerned pupil dilation, eye-lid gap, and eye-movements recorded at 120Hz using the Drowsilogic v 4.3.9. software for each mental state (MW, MB, S).

Time series of physiological signals were extracted over the last 30 seconds preceding probe onset for each trial. Missing data due to eye blinks were linearly interpolated using the most neighboring values. Differences between mental states for each age group were compared using the non-parametric cluster-level permutation test function (alpha-level=0.05, n=1023 permutations) as implemented in the MNE package (version 0.23.0, https://mne.tools/).

The interactions between mental states, age and attentional style on physiological signals over the last 30 seconds of each trial were assessed with linear mixed effect modelling using the lmer function in R and participant defined as random effect.

For post-hoc investigations of the interaction between attentional resources and arousal across mental states and age, physiological signals averaged over the last 30 seconds of each trial were normalized by z-scoring values of each participant. Correlation between ASQ scores and physiological variables across participants for each mental state and age group was assessed with Pearson's correlation tests.

Results

Reportability profiles. All senior participants were free of cognitive decline (MMSE mean score= 29.3±0.8, range= 28-30).

We found a higher occurrence rate of MW over MB and S in both groups (MW vs. MB: z(119,108)=8.14, p<0.001, MW vs. S: z(119,108)=6.12, p<0.001). Post-hoc tests confirmed the higher occurrence of MW over MB and S in senior (Wilcoxon signed-rank test, MW vs. MB: r=0.60, p<0.001, MW vs. S: r=0.62, p<0.001) and in young adults (MW vs. MB: r=0.59, p<0.001, MW vs. S: r=0.62, p<0.001) (Figure 2A).

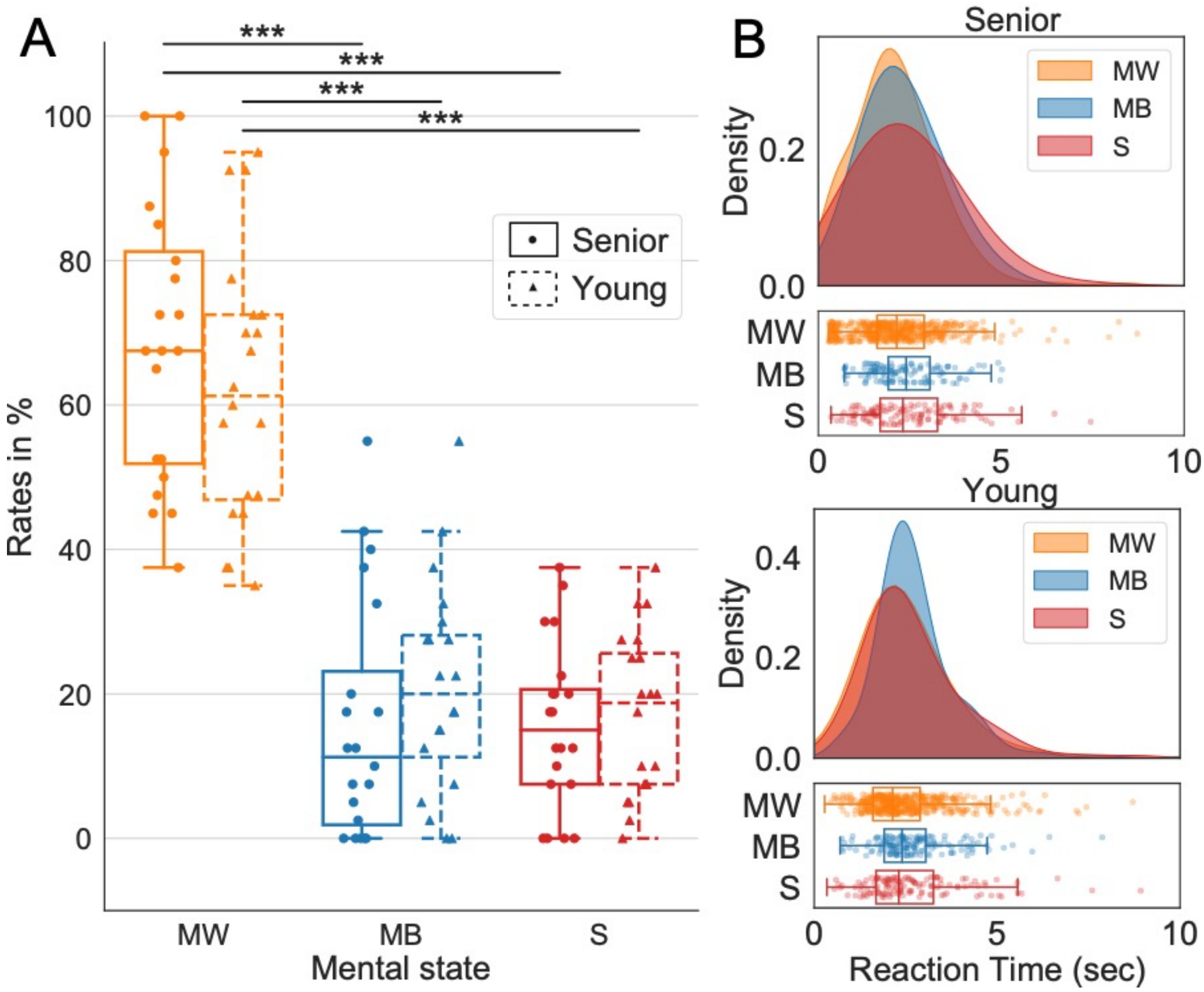

Figure 2. **Mental state reportability in senior and young participants. (A)** Mind-wandering (MW) predominates in all participants independently of age group, which was more prominent in seniors. **(B)** Distribution of reaction times for mental states for senior (upper panel) and young participants (lower panel) shows that MW was reported faster than other mental states, suggesting similar efficiency across age groups. *Notes*: Boxplots: mean (horizontal line), first and third quartile (box), as well as first and ninth deciles (vertical line) for Mind-Wandering (MW, yellow), Mind-Blanking (MB, blue), and Sensations (S, red) represented for senior (solid) and young participants (dotted). Individual data points of each are represented as circles (senior) and triangles (young), ***$p<0.001$ Wilcoxon rank-sum tests. Distribution of reaction times modelled with a continuous probability density curve (kernel density) for each mental state.

A similar MW predominance was revealed with regards to reaction times. MW was reported faster than MB (z(108,40)=-2.78, p=0.005) and S (z(108,40)=-2.09, p=0.037), while MB and S were reported equally fast (z(108,40)=-2.77, p=0.622) (Figure 2B, upper panel). RTs in seniors and young participants did not differ with regards to mental state (seniors vs. young with MW vs. MB: z(108,40)=1.63, p=0.101, MW vs. S: z(108,40)=0.85, p=0.394, MB vs. S: z(108,40)=-0.67, p=0.502), suggesting that mental states were categorized with similar efficiency across age groups (Figure 2B, lower panel).

We finally checked whether mental states were reported differently across time between young and senior participants. We investigated the distribution of mental states over the experiment and found no evidence for unequal distribution of response types over time for all mental states in each age group (Chi-squared tests, p> 0.05) (Figure S1). Probabilities of transition between mental states were also similar across both age groups (Wilcoxon rank-sum tests, p> 0.05) (Figure S2), providing no evidence for changes in the inter-state dynamics across age groups.

Attentional style. Seniors self-reported a lower Attentional Style Questionnaire (ASQ) score than younger participants (37.2±[33.7, 40.7] vs. 46.6±[43.5, 49.7], r=-0.56, p<0.001, Figure 3A), indicating a higher focus ability for senior participants. The interaction between attentional style, mental state reportability, and age group was identified between MW and MB reports (z(108,40)=-6.15, p<0.001), MW and S reports (z(108,40)=5.58, p<0.001) but not between MB and S (z(108,40)=0.381, p=0.703). Therefore, we investigated the association between the ASQ score and the occurrence of spontaneous state reportability across age group.

In seniors, lower ASQ scores were linked to higher MW over MB (z=4.65, p<0.001) and higher MW over S rates (z=2.38, p<0.01) (Figure 3B, left panel). The reverse pattern was found in younger participants who showed that lower ASQ scores were linked to lower MW over MB (z=-4.07, p<0.001) and S rates (z=-5.38, p<0.001) (Figure 3B, right panel), meaning that age reverses the relationship between attentional focus and mental state reportability.

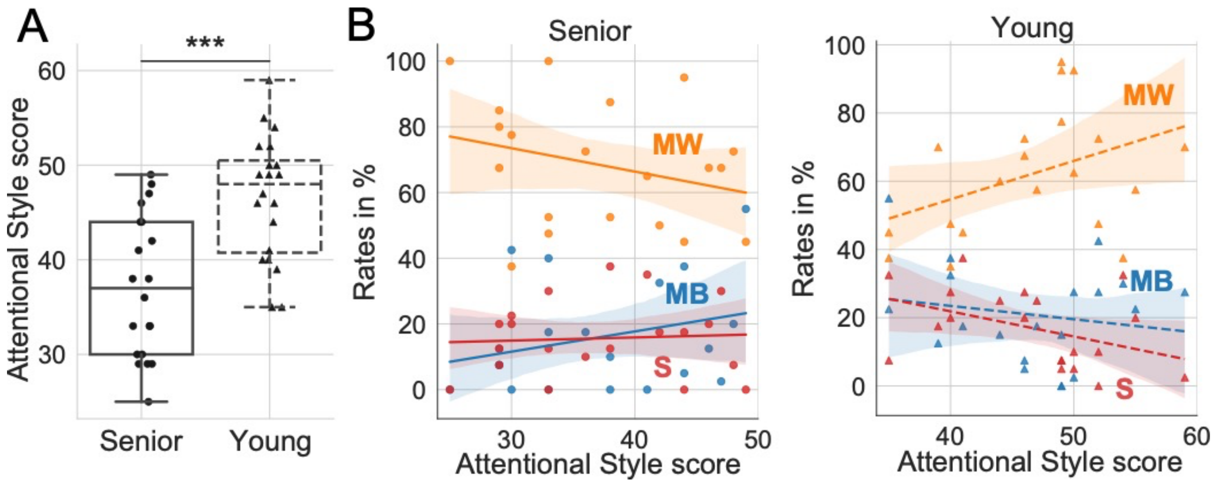

Figure 3. **Attentional style regulates the reportability spontaneous mental states in opposite direction depending on age. (A)** Seniors self-reported lower scores on the Attentional Style Questionnaire (ASQ) than younger participants, indicative of higher attentional focus. (**B**) In seniors, lower ASQ scores were associated with higher MW (left panel) and the reverse pattern was found in younger participants who showed that lower ASQ scores were linked to lower MW (right panel), meaning that age reverses the relationship between attentional focus and mental state reportability. *Notes*: Boxplots: mean (horizontal line) and first and third quartile (box), as well as first and ninth deciles (vertical line) of the Attentional Style Questionnaire (ASQ) score are represented (solid: aged, dotted: young). Individual data points are represented in circles: (senior) and triangles (young). Significant differences across conditions are reported as solid black lines (Wilcoxon rank-sum test, ***p<0.001). Correlation plots: The lines (solid: senior, young: dotted) represent the correlation between the rate of Mind-Wandering (MW): yellow, Mind-Blanking (MB): blue, Sensations (S): red, and the ASQ score with shaded area as confidence intervals for both senior (left panel) and young (right panel) participants. Individual data points of each are represented as circles (senior) and triangles (young).

Then, we checked whether our results based on attentional style could be confounded by the effect of anxiety on the occurrence of mental states. We first confirmed that lower attentional focus (high ASQ score) correlated with higher anxiety scores (Pearson's correlation test: R(37)=0.33, p=0.043, Figure S3). We also found that seniors had a lower anxiety score than young participants (4.58±[2.45, 6.71] vs. 7.25±[4.98, 9.52], r=-0.31, p=0.025) (Figure S4A); however, anxiety scores did not predict significantly rates of mental states nor interacted with the type of mental state and age groups (mixed-model effects: p-values > 0.05) (Figure S4B). This excludes anxiety as a potential confound explaining the influence of attentional style on mental state reportability.

Arousal. Across the experiment, seniors had smaller pupil size when reporting MW than MB ([-30 to 0]s, F=7.93, p=0.004), and MW than S ([-30 to -15.8s]s : F=10.67, p=0.006; [-15.6 to 0]s: F=7.39, p=0.009), while pupil size did not differ in young participants in any time cluster with regards to mental state reportability (Figure 4A). Linear mixed-effects models revealed a significant interaction between age and pupil size difference between MW and MB (t(108,40)=-2.93, p=0.005), as well as between MW and S (t(108,40)=-3.57, p<0.001). These results confirm that physiological signatures of mental state reportability differ with age.

Attentional style furthermore interacted with age groups in predicting the pupil size difference between MW and MB (t(108,40)=-2.25, p=0.028) and between MW and S (t(108,40)=-2.33, p=0.023 Figure 4B). For MW, post-hoc analyses showed that ASQ score correlated negatively with normalized pupil size in senior participants (Pearson's correlation, R=-0.66, p=0.002), but not in young (R(17)=-0.01, p=0.971) (Figure 4C, left panel). For MB, ASQ score correlated positively with pupil size in senior participants (R(13)=0.62, p=0.015), but not in younger adults (R(16)=-0.063, p=0.803) (Figure 3B, middle panel). Finally, a trend for a positive correlation between ASQ and pupil size was also found for S (R(14)=0.44, p=0.092, young: R(17)=-0.34, p=0.161) (Figure 3B, right panel). Overall, these results indicate that the relationship between arousal and mental state is dependent on attentional style specifically in seniors.

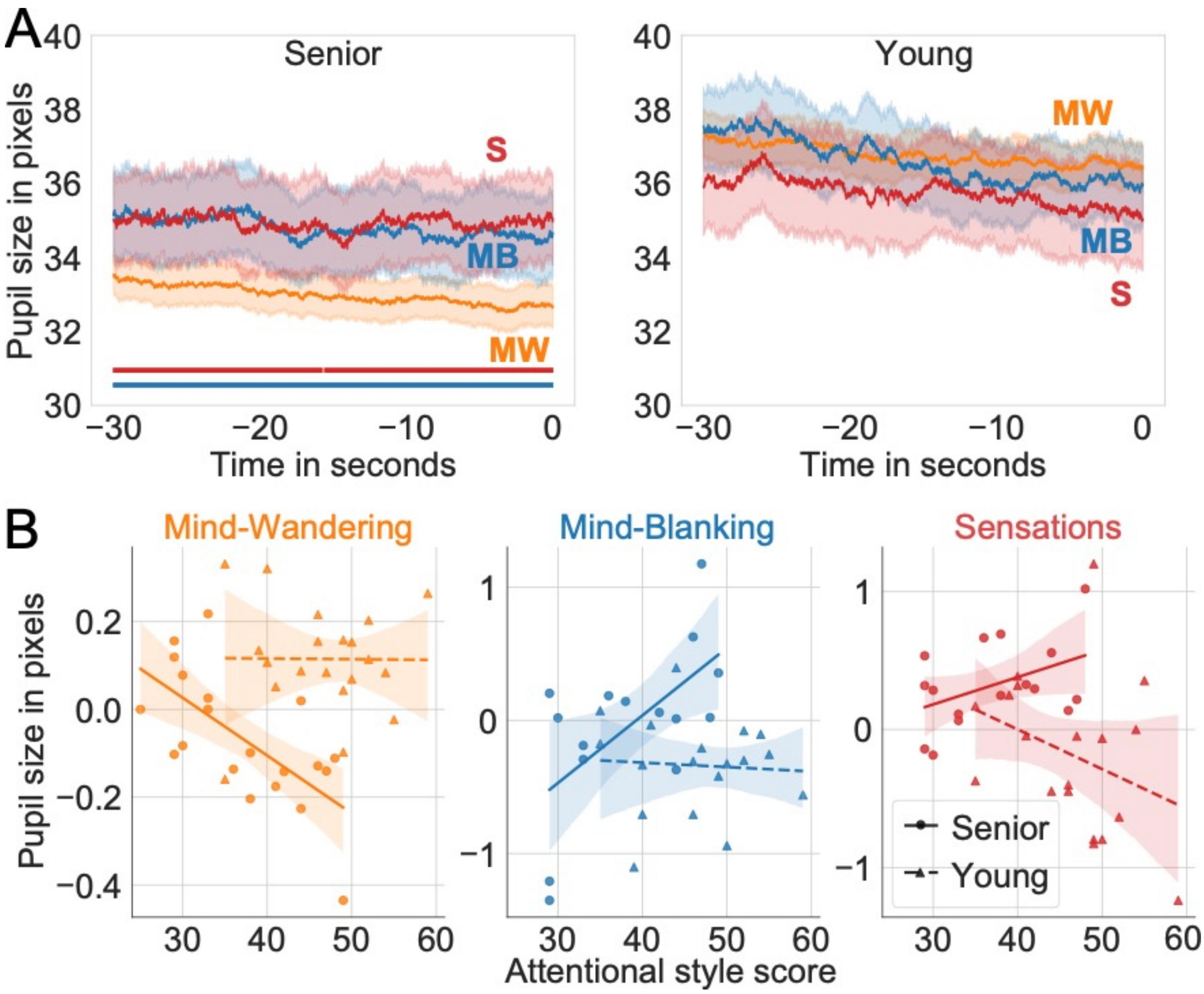

Figure 4. **The relationship between pupil-linked arousal and mental state reportability is dependent on attentional style in seniors but not in young participants. (A)** The time-course of pupil size over thirty seconds preceding sound onset for each mental state showed that seniors had smaller pupil size when reporting mind wandering (MW) and mind blanking (MB) than sensory-related thoughts (S) (left panel). No such differences were found in young (right panel). *Notes*: Mean and confidence intervals are represented respectively with solid line and shaded areas. Clusters of significant difference between mental states are represented by solid lines (MW vs. MB: blue and MW vs. S: red).

(B) Attentional style also interacted with age groups in predicting the pupil size differences, with less focused seniors showing lower pupil size for MW (left panel) and higher pupil size for MB (middle panel), while no such interaction was found in young, showing specific mechanisms by which mental state reportability are jointly regulated by age-dependent attentional style and pupil-linked arousal in seniors. No significant correlations were found for S (right panel). *Notes*: Lines (straight: senior, dotted: young) represent the linear fit for each mental state and shaded areas are confidence intervals. Individual data points are represented as circles (senior) and triangles (young).

We checked whether age-dependent changes in pupil size could be confounded by the variations of eyelid gap and gaze position that have been reported to also predict the occurrence of spontaneous mental states (Grandchamp et al., 2014). Time-resolved analyses of eyelid gap and linear mixed models showed that MB was associated with a smaller eyelid gap in senior in comparison to S ($t(40,108)=-2.32$, $p=0.236$) and to MW ($t(40,108)=-3.01$, $p=0.004$) (Figure S5A). These differences interacted with ASQ scores but not with age (ASQ score for MB vs. MW: $t(40,108)=3.47$, $p<0.001$, ASQ score for MB vs. S: $t(40,108)=2.61$, $p=0.011$, Figure S5B). Gaze position did not predict mental states, nor depended on age and attentional style (Figure S6). These results show that other ocular metrics can add information regarding the occurrence of spontaneous mental states and their interaction with attentional style, but not with age. Thus, they cannot confound the observed pupil size differences across mental states and the reported interaction between age and attentional style.

Discussion

We investigated how attentional style and arousal impact the reportability of spontaneous mental states depending on age. Using an experience-sampling task, we first report higher rates of Mind-Wandering (MW) over Mind-Blanking (MB) and Sensations (S), and we found that the predominance of MW over other mental states depended on the interaction between age and attentional style. This interaction was further observed at the physiological level as pupil size, a proxy of arousal (Bradley et al., 2008; Unsworth & Robison, 2018), correlated with attentional style across spontaneous mental states in senior, but not in young participants. We interpret such differences as reflecting the presence of age-dependent attentional style and arousal regulating the reportability of spontaneous mental states.

Our results first replicated that MW predominates over MB and S reports in both age groups. Such high prevalence of MW is consistent with the fact that this state represents about 30-50% of our mental activity during the day (Killingsworth & Gilbert, 2010). In comparison, MB is a quite rare phenomenon, reported between 8-18% depending on the thought sampling methodology (Ward & Wegner, 2013; Andrillon et al., 2021; Van Calster et al., 2017). The low reports of Sensations found can be explained by the limited visual and auditory stimulations (dim light, black screen and earphones) and task requirements (spontaneous mental state reports) in the methodology here adopted. The stable inter-state dynamics, distribution of mental states and reaction times across age indicate that spontaneous mental states are discriminated similarly in both young and seniors.

We then replicated that seniors had a better engagement in tasks than young adults as revealed with an overall more focused attentional style (Maillet et al., 2020; Moran et al., 2021; Seli et al., 2021). We found, moreover, that a better attentional focus resulted in more MW over other mental states in senior participants, while the opposite was found in the young cohort, *i.e.* there were lower rates of MW reports. To explain this difference in how spontaneous mental states are regulated by attentional style with age, we propose that senior participants benefit from greater attentional focus to remain engaged into MW, while younger participants would be more easily distracted by their internal thoughts, as previously suggested (Moran et al., 2021; Seli et al., 2017, 2021). Importantly, we also replicated the findings that seniors exhibited lower anxiety symptoms (Moran et al., 2021), but found no impact of this variable on spontaneous mental states reportability, showing this was not a confound for the evidence of an age-dependent effect of attentional style on spontaneous mental states.

The presence of a specific regulation of spontaneous mental states in seniors compared to young participants found further support at the physiological level as we found an interaction between arousal and attentional style only in senior participants. Using pupillometry, lower rates of MW in senior participants are associated with lower attentional focus and stronger pupil restriction (low arousal), which can be here explained by the difficulty to voluntarily remain focused or to re-engage with their own mental activity for participants with low attentional resources in the case when arousal is low (Gyurkovics et al., 2018). Conversely, lower attentional focus in seniors correlated with higher pupil dilation (high arousal) during MB reports, which can be interpreted as a result from an enhanced behavioral volatility associated with high arousal and low attentional resources (Andrillon et al., 2019). This contrasts with young participants, whose regulation of mind-wandering would rather be unintentional. As such, reportability of spontaneous mental states would not depend on the availability of attentional resources to voluntarily engage inwards depending on arousal levels, explaining hereby the absence of an interaction between attentional style and arousal.

The origin of these differences in the way attentional style and arousal regulate the reportability of spontaneous mental states might be related to age-dependent changes in the activity of locus coeruleus (LC) (Jepma & Nieuwenhuis, 2011; Larsen & Waters, 2018). LC is a key brain region involved in the regulation of arousal (Sara & Bouret, 2012) and attentional control (Unsworth & Robison, 2017) and regulates pupil size variations by subcortical pathways innervating the iris dilator and sphincter muscles (Mathôt, 2018). LC is also involved in the regulation of spontaneous mental states (Jubera-García et al., 2020; Mittner et al., 2016). Observed age-related reduction in the connectivity of the locus coeruleus with other brain regions and their impact on cognitive functions might thus contribute to the interaction between arousal and attentional style observed in senior participants (Langley et al., 2021). Further studies involving neuroimaging will allow to directly test the structural and functional changes in neural circuits underlying arousal and attentional processes involved in the age-dependent regulation of mental state reportability.

Our results further stress the importance to embrace a comprehensive approach when investigating the reportability of spontaneous mental states and their physiological underpinnings. The relationship between pupil size variations and spontaneous mental states have indeed yielded contrasted results in the literature so far. Some studies reported an increase in pupil size during an episode of MW (Pelagatti et al., 2018; Unsworth & Robison, 2018), while others found opposite results, *i.e.*, a smaller pupil size during MW but in a n=2 participants cohort (Grandchamp et al., 2014). As we observed that pupil size modulation across spontaneous mental states depends on the interaction between the age and the attentional style of participants, our study supports the need to consider age-dependent changes in attentional style and arousal and the multi-faceted nature of spontaneous thinking when studying their psychological and physiological correlates (Robison et al., 2020).

Some limits to the present study deserve to be noted. First, our experience-sampling task allowed us to probe the spontaneous occurrence of mental states in the absence of a cognitive task. Whether the reported impact of age-dependent changes in attentional style and arousal on spontaneous mental states would be also observed in the context of an active task, such as the auto-scrolling text used by Ward & Wegner (2013), remains to be addressed. Second, we improved on previous methodologies by incorporating the difference between MW and MB, allowing for participants to report whether their internal mental content was rich or empty of mental content. Further studies should include finer distinctions between mental states, such as between intentional and unintentional MW, to test whether the regulation of spontaneous mental states by attentional style and arousal rely on voluntary processes in senior participants.

To conclude, our results reveal the impact of attentional mechanisms and arousal on the reportability of spontaneous mental states depending on participants' age. We interpret these age-related differences as reflecting the engagement of specific attentional mechanisms in the aging population, resulting in an opposite modulation of the occurrence of mental state reportability by attentional style across both age groups and a modulation of pupil size variations by attentional resources across spontaneous mental states in senior participants only. Further studies using neuroimaging will allow us to identify the neural circuits that are involved in the age-dependent regulation of the reportability of spontaneous mental state uncovered by this study.

Contributions statement. A. de Beauchamp, C. Bastin and A. Demertzi designed the study. A. de Beauchamp and M. Koroma conducted the research and the analysis helped by S. Mortaheb and P.A. Boulakis. M. Koroma and A. Demertzi wrote the manuscript. All authors reviewed the manuscript.

Competing interests. The authors declare no competing interests.

Data and code availability. All codes and data are freely accessible via the Gitlab (https://gitlab.uliege.be/S.Mortaheb/mb_aging) and OSF server (https://osf.io/mknjr/).

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