2021-11

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Turnbull, A

http://hdl.handle.net/10026.1/18678

10.1016/j.concog.2021.103226
Consciousness and Cognition
Elsevier BV

Age-related Changes in Ongoing Thought Relate to External Context and Individual Cognition

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Acknowledgements

This project was supported by European Research Council Consolidator awarded to Jonny Smallwood (WANDERINGMINDS – 646927).

Keywords: mind wandering, ongoing thought, aging, everyday cognition

Introduction

As we age our patterns of cognition change, and these changes can be detected using laboratory tasks (Drag & Bieliauskas, 2010). Laboratory tasks have been designed and utilized to understand how different aspects of cognition change with age, establishing differential trajectories for different processes. For example, healthy aging is related to systematic changes in memory processes (Craik, Klix, & Hagendorf, 1986; Fraundorf, Hourihan, Peters, & Benjamin, 2019; Spencer & Raz, 1995; Uttl, 2008, 2011): as individuals age, they show deficits in episodic memory (Nilsson, 2003), while often showing preservation in semantic memory (Nyberg, Bäckman, Erngrund, Olofsson, & Nilsson, 1996; Piolino, Desgranges, Benali, & Eustache, 2002). Memory decline is of particular importance in aging research because atypical aging in systems involved in episodic memory, semantic memory, or both, is central to the most common forms of dementia (Hodges, 2000). Aging is also associated with decline in executive control (Bopp & Verhaeghen, 2005; Rey-Mermet & Gade, 2018; Verhaeghen & Cerella, 2002; Wasylyshyn, Verhaeghen, & Sliwinski, 2011). Patterns of day-to-day thinking (Killingsworth & Gilbert, 2010) measured using experience sampling in both the real world and during laboratory tasks have also shown links to laboratory measures of executive control and memory (Ho et al., 2020; Kane et al., 2007; Robison, Miller, & Unsworth, 2020; Turnbull, Wang, Schooler, et al., 2019; H.-T. Wang, Poerio, et al., 2018), suggesting they provide an ecologically valid way of assessing cognitive processes in the real world that are at-risk for cognitive aging. However, it is important to measure ongoing thought along a range of dimensions, as different contents relate uniquely to cognitive traits (H.-T. Wang, Poerio, et al., 2018).

Measures of ongoing thought are also highly context-dependent, for example, when performing tasks that require participants to decide whether specific words refer to themselves or a friend, individuals report patterns of thought dominated by episodic social cognition (Konu et al., 2021). This means that these measures reflect both cognitive traits of the individual as well as the external context, and interactions between the two: for example, off-task thought levels during demanding tasks are negatively related to executive functions (Kane et al., 2007), while off-task thought levels during simple tasks have been associated positively with executive functions (Levinson, Smallwood, & Davidson, 2012) and creativity (Baird et al., 2012). Research shows that individual differences in dimensions of ongoing thought content emerge as a result of cognitive traits interacting with the external context (Smallwood, Nind, & O'Connor, 2009; Turnbull, Wang, Murphy, et al., 2019). These relationships are likely to be complex in the real-world, in which participants are required to engage in and respond to a range of different external contexts. Using measures of ongoing thought to understand aging cognition, therefore, requires a thorough examination of different dimensions of content in a context-dependent framework. Older adults show cognitive decline compared to younger adults, but are also known to engage in different activities that could affect their ongoing thought (Marcum, 2013).

Studies using experience sampling to measure ongoing thought during task performance in laboratory settings has found that older adults consistently report experiences that are more tethered to the immediate environment than their younger counterparts (Irish, Goldberg, Alaeddin, O'Callaghan, & Andrews-Hanna, 2019; Jordão, Ferreira-Santos, Pinho, & St Jacques, 2019; Seli, Maillet, Smilek, Oakman, & Schacter, 2017).

Methodologically, laboratory studies suggest that although aging does not impair the ability to describe thoughts (Arnicane, Oberauer, & Souza, 2020; Frank, Nara, Zavagnin, Touron, & Kane, 2015) there are age-related differences in task motivation (Moran et al., 2021; Seli et al., 2020), computer literacy (Czaja et al., 2006), and question interpretation (McVay, Meier, Touron, & Kane, 2013) that should be considered when exploring self-reported ongoing thought, especially during task performance (Seli, Cheyne, Xu, Purdon, & Smilek, 2015). Despite these concerns, a recent meta-analysis of studies measuring ongoing thought during laboratory task performance found that age-related reductions in mind-wandering were robust to a range of methodological factors. These included how thoughts were reported (self-caught vs. probe-caught), whether "task-related interference" was measured as a separate category of thought, and task demands (Jordão et al., 2019). Subsequent research confirmed that these differences persisted even when motivation was taken into account (Seli et al., 2020). This finding has also been found to hold for both intentional and unintentional mind wandering (Moran et al., 2021; Seli et al., 2017). A similar shift towards on-task thoughts has also been found using daily-life experience sampling (Maillet et al., 2018), alongside differences in thought content (e.g., older adults' thoughts were more positive and interesting). Taken together, this research suggests that experience sampling of ongoing thought is a promising tool for understanding aging cognition that can identify reliable differences in the thoughts of older and younger adults that persist even when accounting for the methodological challenges of comparing these populations, and are similar across both laboratory and real-world settings.

Currently, it is unclear the extent to which these changes reflect i) cognitive aging and ii) changes in context (lifestyle), as few studies have obtained independent measures of cognition and either varied or measured the external context. Moran et al. (2021) found that neither task demands nor executive function abilities related to age-related differences in mind wandering in the laboratory after accounting for motivational differences. McVay et al. (2013) found that differences in mind wandering were more pronounced in tasks that older adults found more challenging, implicating cognitive aging in these differences, while Martinon et al. (2019) found that differences in how cognitive traits interacted with task context were responsible for age-related differences in off-task thought. Finally, Zavagnin, Borella, and De Beni (2014) found that older participants showed an increase in mind wandering specifically in a semantic task compared to the perceptual version of the same task. Taken together, these results suggest that laboratory measures of ongoing thought vary in older adults due to differences in cognitive traits that interact with the external context. It is not yet known how these findings generalize to the real world.

Building on this research, we performed experience sampling of older and younger adults' ongoing thought along multiple dimensions in the real world. To assess how age-related changes in ongoing thought may reflect differences in cognitive traits and changes in lifestyle, we collected independent measures of cognition in the laboratory and sampled the demands of the individuals' external context while they completed ongoing thought probes. We selected cognitive traits that have been used to understand aging cognition in executive functions and memory: a) fluid intelligence (Raven, 1994), which previous research has linked to the context-dependent regulation of ongoing thought (Mrazek et al., 2012; Turnbull, Wang, Schooler, et al., 2019) and shows reductions with age (Staff, Hogan, & Whalley, 2014) and b) semantic and episodic memory using the Autobiographical Interview (AI), which has been used to map the different trajectories of aging in these different memory domains (Levine, Svoboda, Hay, Winocur, and Moscovitch (2002), although see: Renoult et al. (2020) and Strikwerda-Brown, Mothakunnel, Hodges, Piguet, and Irish (2019), for more recent discussions on this measure). We used this data to explore: 1) how the contents of ongoing thought changes with age and 2) how differences in ongoing thought reflect individual differences in participants' cognitive traits measured in the laboratory and/or differences in the demands of activities individuals were performing. We also explored whether any relationships between ongoing thought and i) cognitive traits, ii) context were different in older and younger adults. These analyses were exploratory in nature and were not designed to test specific predictions about links between age-related changes in cognition, context, and ongoing thought. The aim of this study was to ascertain 1) the extent to which age-related changes in ongoing thought may reflect i) cognitive aging and/or ii) contextual changes and 2) whether relationships between ongoing thought and i) cognition and ii) context are age-specific, to inform future research using these methods to understand aging cognition. Combining Multi-dimensional Experience Sampling (MDES) with Principal Components Analysis (PCA) and Linear Mixed Effects modelling allowed us to ascertain how individual differences in specific factors (cognitive traits and the environment) relate to differences in the thoughts people have within a common multi-dimensional space. This accounts for the fact that different individuals contribute differently to the outcome of the PCA due to factors that we are modelling (e.g., different cognitive traits) as well as factors not considered in our analysis, including noise and methodological bias (e.g., answering more probes). There are likely factors we are not accounting for that contribute to the final PCA components meaning that these components do not represent a ground truth space for all individuals. Nevertheless, any relationships to objective measures of cognition, age, and contexts helps us know which variance in PCA space is meaningful in relation to how the covariation in response described by the PCA relate to the explanatory variables of interest. We also wanted to determine the extent to which the structure of ongoing thought was similar in older and younger adults, which is important in determining if this approach to combining MDES with PCA is reliable for understanding aging cognition.

Methods

Participants and procedure

Participants were 78 young adults (M_{age} = 19.64, *SD* = 1.62, Range: 18-27) and 35 older adults (M_{age} = 66.80, *SD* = 6.88 Range: 55-87) who were healthy, right-handed, native English speakers with no history of psychiatric or neurological illness. Young adults were recruited from undergraduate and postgraduate student bodies at the University of York; older adults were recruited through local advertisements, mailing lists, and referrals. The study was approved by the University of York Department of Psychology ethics committee. All participants gave written informed consent prior to participation and were debriefed upon completion. Participants were compensated for their time either financially or by receiving course credit.

Participants formed part of a larger cohort, and previous studies have compared laboratory measures between older and younger adults (Martinon et al., 2019), and assessed laboratory measures extensively in younger adults alone (Poerio et al., 2017; Turnbull, Wang, Schooler, et al., 2019; Vatansever, Bozhilova, Asherson, & Smallwood, 2018; H.-T. Wang, Poerio, et al., 2018), but only a subset of the cohort completed the daily life experience-sampling measures used here. The experience-sampling data from the young but not older adult sample has been reported previously (Ho et al., 2020). This previous study included only 13 questions in their analysis, to allow for clearer comparisons with laboratory measures. As the goal of this study was to perform a comprehensive assessment of differences in ongoing thought between younger and older adults, we included all 20 questions on thought content. As part of the larger cohort study, participants performed a range of cognitive tasks, as described in H.-T. Wang, Poerio, et al. (2018), designed to assess a broad range of cognitive abilities. Tasks were performed over three days, and the order of both tasks and sessions was counterbalanced across individuals. For the purposes of this study, we wanted to examine age-related differences in ongoing thought in daily life and how this might vary according to (1) environmental context and (2) cognitive performance in domains which show varied developmental trajectories in healthy aging. To this end, we included the Autobiographical Interview (AI: Levine et al. (2002)) as a measure of episodic and semantic memory, and the Raven's Advanced Progressive Matrices (RAPM: Raven (1994)) as a measure of fluid intelligence. Cognitive measures were completed first by participants under laboratory conditions after which participants underwent the week-long experience-sampling protocol.

Daily life experience-sampling protocol and measures

Participants reported the content and form of their momentary thoughts as well as the context in which they occurred using a signal-contingent experience-sampling (Wheeler & Reis, 1991) protocol over one week with mobile phones. Signals were scheduled via SurveySignal Software (Hofmann & Patel, 2015) to occur five times daily at quasi-random intervals between 09:00 and 21:00 with at least 30 minutes between consecutive signals. Participants with smartphones were sent signals via text message, which contained a link to an online questionnaire created in Qualtrics. Participants had two hours to answer the questionnaire before the link expired. Twenty-three older adults who did not have smartphones were provided with a mobile phone to deliver signals and paper versions of the questionnaires to complete and return via post at the end of the sampling period. To assess whether method of collection significantly impacted the final thought components, PCA analysis was run separately in participants that completed paper and smartphone versions of the probes. These data were then merged into a single variable, and the correlation between component scores calculated using collection methods separately and together were compared. The results of these correlations were: Component 1 ($r(3026) = 0.915$, $p < .001$), Component 2 ($r(3026) = 0.959$, $p < .001$), Component 3 ($r(3026) = 0.880$, $p < .001$), Component 4 ($r(3026) = 0.888$, $p < .001$), Component 5 ($r(3026) = 0.799$, $p < .001$), suggesting that method of collection did not significantly impact the final thought components. Scatterplots for these results are shown in Supplementary Figure 1. Original PCA components were used for all follow-up analyses.

On average, participants answered 26.80 (*SD* = 8.20) questionnaires (younger adults: *M* = 25.73, *SD* = 6.93; older adults: *M* = 29.17, *SD* = 10.22). Three older adults completed more than 35 surveys because the experience-sampling protocol was initially more intensive (8 signals over 10 days) but was shortened to reduce participant burden. To assess whether these participants significantly impacted the final results, PCA analysis was run without these participants: the correlation between component scores with and without these participants was: Component 1 ($r(2872) = 0.912$, $p < .001$), Component 2 ($r(2872) = 0.989$, p

< .001), Component 3 ($r(2872) = 0.934$, $p < .001$), Component 4 ($r(2872) = 0.789$, $p < .001$), Component 5 ($r(2872) = 0.807$, $p < .001$), suggesting participants who completed the intensive protocol did not disproportionately impact the results. Scatterplots for these results are shown in Supplementary Figure 2. Overall, these means corresponded to average compliance rates of 73.52% (*SD* = 0.20) for younger adults and 76.28% (*SD* = 0.21) for older adults. An independent samples t-test suggested that there was no significant difference in compliance for younger and older adults ($t = -0.673$, $p = .502$, 95%CI[-0.109, 0.054]). These levels of compliance are in line with averages from meta-analyses of experience sampling studies (Rintala, Wampers, Myin-Germeys, & Viechtbauer, 2019, 2020).

Each questionnaire asked participants to first report on the content and form of their ongoing thought immediately prior to the signal. Participants rated their thoughts along 20 dimensions including relationship to goals, social content, form (images, words), and temporal focus on 5-point scales (see Table 1). The four questions indexing the relationship between thoughts and current/future goals were always asked first, followed by the remaining 16 questions on the content and characteristics of thoughts, which were presented randomly. Participants also rated the extent to which their current activity was challenging and required concentration (Table 1) on an increasing scale from 1 to 5. Several other questions were also asked (e.g., current emotions) which are not the focus of the current investigation. Descriptive statistics can be seen in Table 2.

Table 1.

Multi-dimensional experience sampling questions

Thoughts			
Label	**Question**	**Low (1)**	**High (5)**
Focus	My thoughts were related to my current activity and/or external environment	Not at all	Completely
Conflicting	My thoughts were conflicting/interfering with what I am trying to achieve right now	Not at all	Completely
Current goals	My thoughts were helpful for goals that I am trying to achieve right now	Not at all	Completely
Future goals	My thoughts were helpful for goals that I am trying to achieve (or avoid) in the future	Not at all	Completely
Close other	My thoughts involved other people close to me	Not at all	Completely
Distant other	My thoughts involved other people NOT close to me	Not at all	Completely
Self	My thoughts involved myself	Not at all	Completely
Future	My thoughts were about the future	Not at all	Completely
Past	My thoughts were about the past	Not at all	Completely
Important	The content of my thoughts is important to me (i.e., it deals with something important in my life)	Not at all	Completely
Control	I was trying to control the progression of my thoughts	Not at all	Completely
Wanted	I wanted to have my thoughts	Not at all	Completely

Evolving	My thoughts tended to evolve in a series of steps	Not at all	Completely
Repetitive	My thoughts had recurrent themes similar to those that I have had before	Not at all	Completely
Images	My thoughts were in the form of visual images	Not at all	Completely
Words	My thoughts were in the form of words	Not at all	Completely
Specific	My thoughts were detailed and specific	Not at all	Completely
Vivid	My thoughts were vivid	Not at all	Completely
Emotion	My thoughts were....	Very negative*	Very positive*
Deliberate	My thoughts were....	Completely spontaneous*	Completely deliberate*
Context			
Label	**Question**	**Low (1)**	**High (5)**
Challenging	How challenging is what you're doing?	Not at all	Extremely
Concentrate	How much do you have to concentrate on what you're doing?	Not at all	Extremely

*Emotion and Deliberate questions were measured on a scale from 1 (low) to 7 (high)

Behavioural measures

Episodic and semantic memory

The AI was used to assess episodic and semantic memory; it was completed by 65 younger adults (83%) and 34 older adults (97%) in our sample. The AI was conducted as explained in Poerio et al. (2017). Participants completed an adapted version of the AI (Madore, Gaesser, & Schacter, 2014), in which they were shown a random selection of six pictures (from a larger set of 18). These were used as cues to recall an autobiographical event from the past few years. Participants were instructed to describe this specific event in detail from a first-person perspective. They were given 3 minutes to write down as much detail about the event as they could. Responses were scored using the adapted AI scoring manual (Addis, Wong, & Schacter, 2008).This system gave a score for each event regarding internal event details (i.e. episodic details regarding the event including place, time, sensory and mental state details) and external event details (i.e. non-episodic details such as semantic statements and repetitive or off-topic details). These scores were averaged for each participant across each of the six descriptions. A random 25% of the event descriptions were second coded by an independent rater; inter-rater reliability was calculated with intra-class correlation coefficient (two-way random). The reliability coefficient was 0.89 for internal details, 0.86 for external details, indicating excellent interrater reliability (Hallgren, 2012). Internal detail score was used as a measure of episodic memory and external detail score was used to measure non-episodic, semantic memory, that may also have included irrelevant and tangential episodic and semantic information (Renoult et al., 2020; Strikwerda-Brown et al., 2019). Two participants were identified as having extreme values for semantic memory, defined using boxplots in SPSS Statistics (Version 26) as having a score more than 3x the interquartile range outside of the box (i.e. either side of the lower and upper quartile), and were replaced with the median (Leys, Ley, Klein, Bernard, & Licata, 2013). Descriptive statistics can be seen in Table 2.

Fluid intelligence

A computerized version of Raven's Matrices (RAPM; (Raven, 1994) measured non-verbal fluid intelligence. Participants were required to select an object that completed a visuospatial pattern for a set of problems which progressively increased in difficulty. For each problem a set of nine boxes (ordered in a 3x3 design) were shown on screen, with all but one box containing a pattern. Four additional boxes were displayed at the bottom of the screen, each containing a unique pattern. Participants selected which, out of these four pattern options, would best complete the pattern displayed on screen and go in the empty box. Participants first undertook a practice phase where they completed two problems with feedback outlining whether their response was correct and, if not, how they should decide which box was the correct answer. They then completed the full test with no feedback. 34 older adults completed this task using a version where they were given 10 minutes to complete as many of 18 problems as they could, one older adult had missing data for this task. 40 (51%) of the younger adults also completed this version of the RAPM task, while the remaining 38 younger adults completed a longer 20-minute version of the test containing 36 problems. To test whether proportional scores (total correct out of total problems) from the test using 18 and 36 problems were statistically similar, we used a two sample Kolmogorov-Smirnov test to compare younger adults that completed each version (N = 40 for 18 problems, N = 38 for 36 problems). This test was non-significant ($D = 0.184$, $p = .523$), suggesting that the two samples were likely to have come from the same distribution. We therefore used the proportion of correct scores (either out of 36 or 18) for all analyses, resulting in N = 34 older adults and N = 78 younger adults. Descriptive statistics can be seen in Table 2.

Statistical analysis: Principal component analysis

All statistical analyses were carried out in SPSS Statistics (Version 26). Following previous studies (Ho et al., 2020; Martinon et al., 2019; Poerio et al., 2017; Sormaz et al., 2018; Turnbull, Wang, Schooler, et al., 2019; Vatansever et al., 2018; Villena-Gonzalez et al., 2018), data were concatenated into a single spreadsheet with one row representing one experience-sampling response. We applied Principal Component Analysis (PCA) with varimax rotation to the 20 experience-sampling dimensions. Components were selected based on having an eigenvalue greater than 1.

As this is one of the first studies to perform real-world MDES combined with PCA to identify the structure of thoughts in the real world, we wanted to assess the effect of using concatenated repeated measures data with different numbers of observations across participants in the PCA analysis. Having independent observations is not an assumption of PCA, per se, since it is a dimensionality reduction technique rather than an inferential technique (Jolliffe & Cadima, 2016). Nonetheless, we wanted to understand whether the patterns described by the PCA components changes when we allow participants to contribute different numbers of cases to the overall solution. For example, it may be that certain individuals contribute more to the final PCA components than others, either via meaningfully demonstrating a larger degree of certain patterns of thought or by having more observations (i.e., answering more probes). It is also possible that these factors interact, for example, if individuals who demonstrate specific patterns of thought are more likely to answer probes and show a specific cognitive profile. To assess the impact of within-person variability on the final thought components, we compared the original PCA (performed with concatenated data and then averaged within participants) with a methodologically identical PCA performed on participants' averaged probe scores on the 20 thought questions. While a PCA performed on the averaged thought scores has far fewer observations (one per person), making the PCA components less stable, this analysis gives an estimate of the extent to which each component is biased by different numbers of observations. This latter PCA (using averaged thought scores) produced 6 components, and a comparison of the original PCA scores across individuals suggested a strong correspondence for the first four components of thought identified in our original analysis: Component 1 ($r(111) = 0.73$, $p < .001$), Component 2 ($r(111) = 0.87$, $p < .001$), Component 3 ($r(111) = 0.87$, $p < .001$), and Component 4 ($r(111) = 0.80$, $p < .001$). Component 5 showed the lowest correspondence ($r(111) = 0.56$, $p < .001$). This suggests that either Component 5 in the original analysis is less stable, implied by the fact that it explained the least variance, or that it is most affected by the inclusion of non-independent observations. Additionally, the PCA analysis on the averaged thought scores produced a component characterized predominantly by deliberate thought that was not present in the original PCA. Overall, this analysis suggests that although some components of thought are more affected by the inclusion of non-independent observations with different numbers of probes across individuals, the majority show a high degree of similarity with solutions that are produced by analysis of the trial level or using aggregated scores. However, it is important to note that any conclusion made when interpreting results relating to Component 5 (with the lowest similarity between methods as well as the lowest explained variance) should be made with caution.

In addition to the thought scores, the measures of context (how challenging the participants current activity was and how much concentration it required) were also entered into a PCA with varimax rotation to see if they captured highly overlapping variance, and could be combined to ease interpretation. This PCA produced one component that explained 86% of the variance in these scores and loaded positively and equally (.928) on both questions. The score representing the shared variance captured by this component was used in the LMMs and is referred to as “context”.

Statistical analysis: T-tests of covariates

Independent samples t-tests assessed whether there were significant differences in cognitive behavioral measures between young and old age groups. All participants with scores for the measure of interest were included in this analysis (RAPM: 78 young adults, 34 old adults; AI: 65 young adults, 34 old adults). All Levene’s Tests for Equality of Variance were non-significant ($ps > .05$), suggesting the assumption of homoscedasticity was met.

Statistical analysis: Repeated measures ANOVA

A rmANOVA was used to identify if there was an age*component interaction, to determine whether patterns of thought were different between each age group. This was motivated by a desire to look at between-group differences across different components, which could not be assessed using linear mixed models. We aggregated the scores for the five PCA components within each participant to provide a single score representing how much they had exhibited each pattern of thought over the experience-sampling period.

These five aggregated factor scores were entered as dependent variables into an rmANOVA, with the age group (0 = older adults, 1 = younger adults) as a fixed factor. Mauchly's Test of Sphericity was significant (p = .026), suggesting sphericity cannot be assumed. The Greenhouse-Geisser correction was used to appropriately alter the degrees of freedom to account for the violation of sphericity. Following this, rmANOVAs were performed on each age group separately, with post-hoc tests to assess the patterns of thinking within each group. These tests were Bonferroni corrected for multiple comparisons. For young adults, Mauchly's Test of Sphericity was non-significant (p = .109), so no correction was used. For older adults Mauchly's Test of Sphericity was significant (p = .017) and the Greenhouse-Geisser correction was used.

Statistical analysis: Linear mixed models

Experience-sampling data were analyzed using the MIXED procedure in SPSS. The data had a two-level structure in which experience-sampling responses collected over the week (Level-1) were nested within individuals (Level-2). Level-1 dependent variables were PCA component loadings for each of our five thought components; the level-1 independent variable was the component loading of "context" which was group-mean centered prior to analysis (Enders & Tofighi, 2007). Level-2 variables (cognitive performance scores) were z-scored prior to analysis and were entered simultaneously in all models. Multi-level regression models were conducted to examine: (1) relationships between thought components and context, fluid intelligence, and memory, (2) 2-way interactions between context and age group, and cognitive scores and age group and (3) 3-way interactions between context, age group, and each of the Level-2 cognitive measures. Intercepts and slopes were allowed to vary (unstructured covariance matrix; UN), the non-independence of observations within individuals was modeled by fitting an autoregressive correlation structure (AR1) to the Level-1 residuals, and the estimation method was maximum likelihood (ML).

Table 2.

Descriptive statistics

Variable	N	Mean	SD
Focus	113	3.44	1.41
Conflicting	113	1.65	1.04
Current goals	113	2.59	1.42
Future goals	113	2.48	1.37
Close other	113	2.38	1.47
Distant other	113	1.85	1.25
Self	113	3.08	1.31
Future	113	2.71	1.35
Past	113	1.78	1.09
Important	113	2.82	1.24
Control	113	2.09	1.20
Wanted	113	3.14	1.19
Evolving	113	2.51	1.16
Repetitive	113	2.63	1.17
Images	113	2.58	1.23
Words	113	2.84	1.29
Specific	113	3.03	1.10
Vivid	113	2.72	1.15
Emotion	113	4.66	1.50
Deliberate	113	4.19	1.79
Challenging	113	1.96	1.11
Concentrate	113	2.41	1.20
RAPM proportion correct	112	0.52	0.18
AI internal details	99	19.8	8.23
AI external details	99	6.46	5.35

Results

Principal Component Analysis identifies 5 components of thought

To identify patterns of thought across the sample, we first performed a PCA on the experience-sampling responses. This resulted in five components of thought (see Figure 1), defined in order of decreasing variance explained as: "deliberate, external goal-directed thought", "off-task, important, future, self-related thought", "positive, present, goal-pursuit", "vivid imagery", and "past, other-related thought". The eigenvalues and variance explained by each component can be seen in Table 3, and the component loadings are present in Table 4 and illustrated in word clouds in Figure 1. These components are similar to those identified in laboratory (Turnbull, Wang, Murphy, et al., 2019) and daily life (Ho et al., 2020) studies using the same technique on a smaller set of questions (13 compared to 20) in only younger adults, in that components emerged that were largely driven by off-task, self-relevant experience (Component 2 here), the difference between thinking in images and words (Component 4), emotional valence (Component 3), and task-relevant detail (Component 1). Including more questions adults did lead to some differences: Component 3 related clearly to positive emotional valence, but also the extent to which thoughts were rated as wanted and non-conflicting (questions not in previous studies). Future, self-relevant cognition (Component 2) was separated from past-related cognition, which largely formed its own component with thoughts about distant others (Component 5). This latter component was absent from studies with four factor solutions.

Table 3.

Eigenvalues and variance explained by each component

Component	Eigenvalue	Variance explained	Cumulative
1	4.286	21.431	21.431
2	2.339	11.694	33.125
3	1.708	8.541	41.666
4	1.482	7.409	49.074
5	1.032	5.161	54.235

To understand whether these components represented components that were shared by both age groups, we performed the same decomposition in younger and older adults separately, combining the results (see Supplementary Figure 3), and performed a Pearson's correlation of the scores across samples, comparing the scores calculated using each group separately to the scores from the original PCA including all individuals. We visually inspected the output to match the components to those that were most similar, and used absolute correlation values as the direction of the components is arbitrary. The PCA components calculated in both groups separately showed high similarity to the PCA components calculated in the group as a whole, and there was a strong correspondence between the scores for the unique components and the shared components, suggesting the structure of ongoing thought was similar across age groups. The results of these correlations were: Component 1 ($r(3026) = 0.937$, $p < .001$), Component 2 ($r(3026) = 0.979$, $p < .001$), Component 3 ($r(3026) = 0.877$, $p < .001$), Component 4 ($r(3026) = 0.929$, $p < .001$), Component 5 ($r(3026) = 0.880$, $p < .001$).

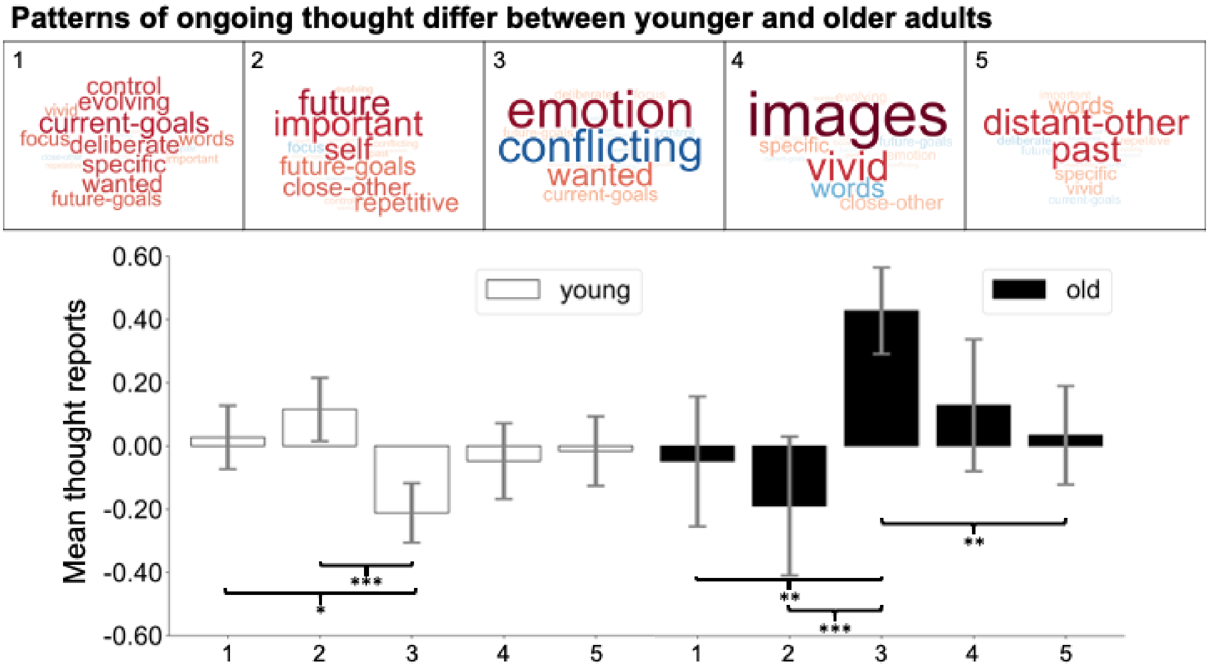

Figure 1. Principal component analysis revealed five dimensions of ongoing thought, represented as wordclouds. The size of the word corresponds to the magnitude of the loading, and the colour to the direction (red: positive loading; blue: negative loading). Repeated measures ANOVAs demonstrated that the extent to which participants engaged in these dimensions differed between old and young adults, with old adults spending more time thinking positive, wanted thoughts compared to other dimensions. Younger adults thought less of these thoughts than those unrelated to their current task consisting of contents about the future and themselves that they deemed important. ***$p < .001$; **$p < .01$; *$p < .05$. As this figure shows the results of rmANOVAs, asterisks denote within-subject effects.

Table 4.

Component loadings for the five-factor solution to a Principal Component Analysis

Labels	Component 1	Component 2	Component 3	Component 4	Component 5
Current goals	0.698	0.095	0.306	-0.104	-0.162
Evolving	0.638	0.247	-0.079	0.165	0.096
Control	0.622	0.198	-0.193	-0.027	-0.104
Specific	0.617	0.111	0.08	0.324	0.265
Deliberate	0.608	-0.006	0.199	-0.035	-0.23
Wanted	0.592	0.112	0.511	0.128	0.036
Future goals	0.528	0.476	0.191	-0.191	-0.1
Focus	0.528	-0.286	0.165	0.124	0.035
Words	0.469	0.054	-0.147	-0.444	0.351
Future	0.11	0.737	-0.014	-0.05	-0.165
Important	0.258	0.669	0.077	0.057	0.165
Self	0.01	0.64	-0.138	0.066	-0.126
Close other	-0.176	0.544	0.128	0.277	0.113
Repetitive	0.177	0.511	-0.079	0.042	0.201
Emotion	0.064	0.11	0.778	0.152	-0.066
Conflicting	-0.107	0.204	-0.74	0.078	0.011
Images	0.038	0.095	0.046	0.863	-0.032
Vivid	0.426	0.111	0.002	0.638	0.274
Past	-0.158	0.219	-0.12	0.126	0.643
Distant other	0.006	-0.135	0.04	-0.033	0.642

Patterns of thinking vary between younger and older adults

Before establishing whether dimensions of thought varied across age groups, we wanted to understand whether the patterns of thought within individuals were different in older and younger adults. We performed a mixed model rmANOVA with the five dimensions of thought as dependent variables and age as a fixed factor. This identified a significant age*factor interaction ($F(3.736,414.727) = 13.272$, $p < .001$, $\eta^2_p = 0.107$), suggesting that the pattern of thoughts within individuals was different for older and younger adults. To understand these patterns, we performed two separate rmANOVAs, one for each age group, with Bonferroni corrected post-hoc t-tests to understand which thoughts individuals spent the most time thinking within each age group (see Figure 1). For young adults, there was a significant effect of component ($F(4,308) = 4.935$, $p = .001$, $\eta^2_p = 0.060$), which was related to significantly more ($\Delta M = 0.239$, $p = .024$, 95%CI[0.019, 0.459] component 1 (deliberate, external goal-directed thought: $M = 0.027$, $SE = 0.051$, 95%CI[-0.075, 0.130]) than component 3 (positive, present, goal-pursuit: $M = -0.212$, $SE = 0.048$, 95%CI[-0.307, 0.116]), as well as significantly more ($\Delta M = 0.327$, $p < .001$) component 2 (off-task, important, future, self-related thought: $M = 0.116$, $SE = 0.051$, 95%CI[0.014, 0.218]) than component 3. Older adults also showed a significant effect of component ($F(3.117,105.992) = 8.689$, $p < .001$, $\eta^2_p = 0.204$). This was related to significantly more ($\Delta M = 0.477$, $p = .007$, 95%CI[0.092, 0.861]) component 3 ($M = 0.428$, $SE = 0.070$, 95%CI[0.286, 0.570]) than component 1 ($M = -0.049$, $SE = 0.105$, 95%CI[-0.262, 0.165], as well as more ($\Delta M = 0.617$, $p < .001$, 95%CI[0.252, 0.982]) component 3 than component 2 ($M = -0.189$, $SE = 0.112$, 95%CI[-0.417, 0.039]), and more ($\Delta M = 0.394$, $p = .004$, 95%CI=[0.093, 0.695]) component 3 than component 5 (past, other-related thought: $M = 0.034$, $SE = 0.079$, 95%CI[-0.127, 0.195]). The differences between age groups appears to be predominantly driven by the degree to which participants engaged in positive, present, goal-pursuit: younger adults engaged in this less than other types of thinking whereas older adults engaged in this more.

Age relates to differences in cognitive resources

To understand how age related to cognitive resources in different domains, we compared old and young groups on measures of semantic and episodic memory, and fluid intelligence (see Figure 2). Older adults had significantly lower episodic memory ($t(97) = 8.010$, $p < .001$: Young: $M = 23.55$, $SD = 6.68$; Old: $M = 12.68$, $SD = 5.86$) and fluid intelligence ($t(110) = 7.793$, $p < .001$: Young: $M = .59$, $SD = .15$; Old: $M = .37$, $SD = .13$), but significantly higher semantic memory scores ($t(97) = -2.019$, $p = .046$: Young: $M = 5.68$, $SD = 5.20$; Old: $M = 7.94$, $SD = 5.42$). This fits well with previous research showing that fluid intelligence and episodic memory decline in later life, but that semantic memory is preserved or even enhanced in tests relying on accumulated knowledge (Nyberg et al., 1996). However, it is important to note that recent findings suggest caution in interpreting external details in the AI as reflecting semantic cognition (Renoult et al., 2020; Strikwerda-Brown et al., 2019). These details include non-semantic information, and increases could also occur due to poor inhibition of irrelevant details during the AI.

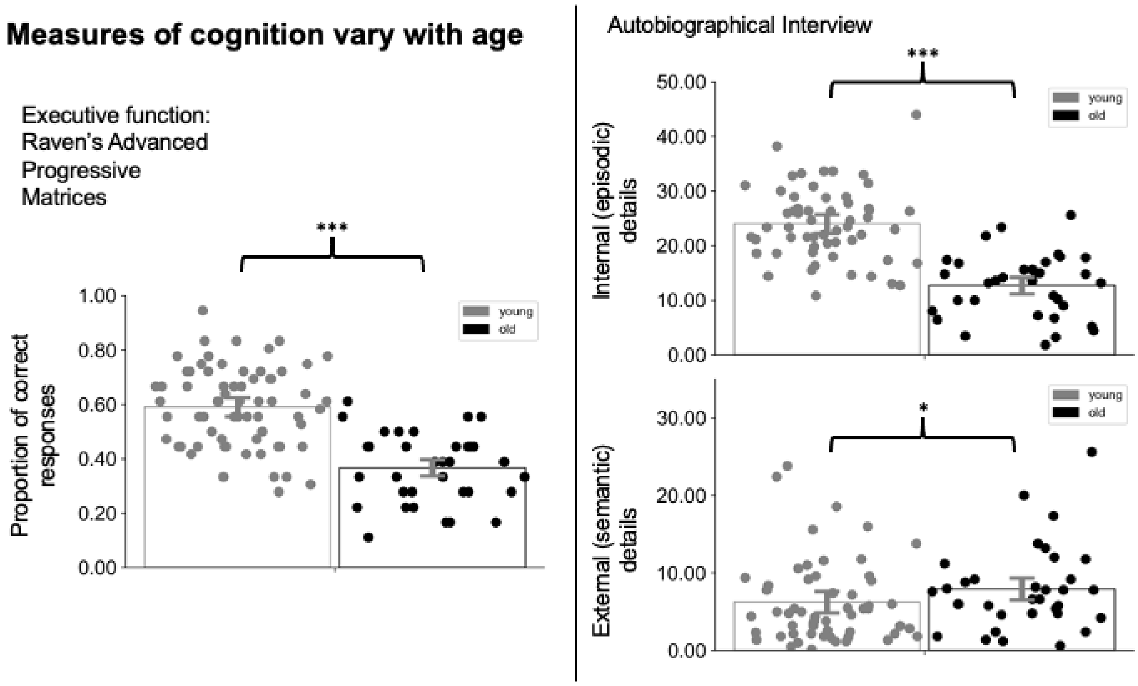

Figure 2. Older adults showed significant performance differences on measures of executive function and memory compared to younger adults. Specifically, older adults had a lower accuracy on Raven's Advanced Progressive Matrices, a measure of fluid intelligence. Older adults also recalled less internal, episodic details during the Autobiographical Memory Interview, but more external, semantic details than participants in the younger age group. Between-group significance from t-tests are shown asterisks: ****p* < .001; ***p* < .01; **p* < .05.

Understanding the contribution of cognition and context to age-related changes in thought

To understand the relationship between age and each thought dimension, we performed a series of linear mixed effects models, with each component (thought dimension) as the dependent variable and age, context, RAPM, and episodic and semantic AI scores as predictors. We modelled several effects to better unpack the data. First, to understand these dimensions of thought, we included main effects of the fluid intelligence and memory, as well as a main effect of context. Second, to understand how age affected each thought dimension, we included a main effect of age. Finally, to understand how age was impacting each thought dimension, we modelled age*context, age*cognition (fluid intelligence, semantic, and episodic memory), and age*context*cognition interactions.

Do components of thought relate to measures of cognitive resources?

To better understand these dimensions of thought, we modelled main effects of the cognitive measures on each thought component. One significant effect emerged: RAPM scores had a significant relationship to component 2 ($F(1, 96) = 4.85$, $p = .030$). The estimate of this effect showed that it was negative ($\beta = -.18$, SE = .12, $t(95) = -1.53$, $p = .130$, 95%CI[-0.42, 0.05]), but no longer significant suggesting that this effect may not hold when controlling for the other variables in the model. This suggests that people with higher fluid intelligence typically engaged less in off-task, important, future, self-related thought, implicating this thought component with problems of executive control (Kane et al., 2007), although this effect may not hold when accounting for the other predictors.

Do components of thought vary according to the external context?

To ensure that results were not driven by age group differences in the extent to which individuals engaged in challenging activities that required concentration, we performed a linear mixed effects model with context as the dependent variable and age group as a fixed factor. There was no effect of age on context ($\beta = -.003$, SE = .07, $t(105) = -$

0.45, *p* = .964, 95%CI[-0.15, 0.14]), suggesting younger and older adults engaged in similarly challenging activities.

To understand how each component changed according to context difficulty, we modelled the main effect of context. Across the whole sample, the fixed effect of context was significant for component 1 (β = .55, SE = .08, $t(116)$ = 7.00, $p < .001$, 95%CI[0.39, 0.71]), indicating that during more demanding daily life activities individuals engaged in more deliberate external goal-directed thought(see Figure 3). This implicates thought component 1 in external task performance.

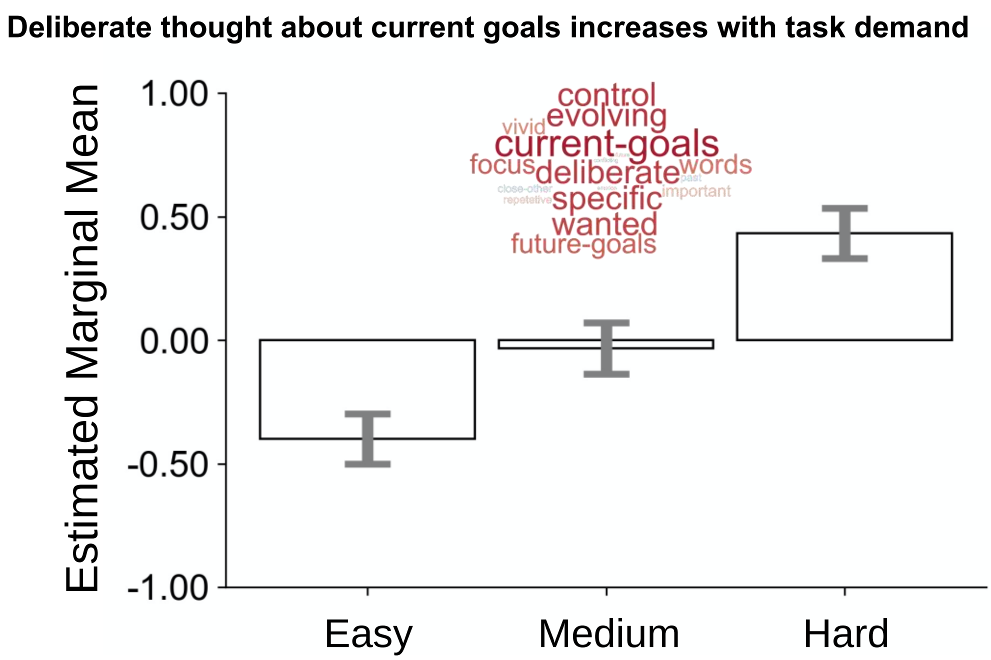

Figure 3. A linear mixed effects model for deliberate thinking about current task goals showed a main effect of context, such that across both age groups this type of thinking was related to increasing external task difficulty. Plotting estimated marginal means from this model shows that this type of thinking occurs more during hard external tasks that require concentration.

How does age relate to each component of thought?

Having established that patterns of thinking were different within older and younger adults, we wanted to understand specifically how age affected each dimension whilst accounting for differences in cognitive resources and context (see Figure 4). Fixed effects of age were significant for Component 2 (β = .49, SE = .18, $t(99) = 2.75$, $p = .007$, 95%CI[0.14, 0.85]) and Component 3 (β = -.57, SE = .15, $t(99) = -3.78$, $p < .001$, 95%CI[-0.87, -0.27]). Estimated marginal means show that: (1) younger adults typically do more of component 2 thinking (off-task, important, future, self-related thought) compared to older adults (Young: *M* = .12, *SE* = .08, 95%CI[-0.03, 0.28]; Old: *M* = -.37, *SE* = .16, 95%CI[-0.69, -0.06]) and (2) older adults do more of component 3 thinking (engaged in positive, present goal-pursuit) compared to younger adults (Young: *M* = -.23, *SE* = .07, 95%CI[-0.36, -0.10]; Old: *M* = .35, *SE* = .14, 95%CI[0.08, 0.62]). This is in line with research showing that older adults mind wander less than younger adults (Jordão et al., 2019; Maillet et al., 2018), as well as some studies suggesting an age-related reduction in “future thinking” (Giambra (1989); Irish et al. (2019); Jackson and Balota (2012), although see: Gardner and Ascoli (2015); Maillet et al. (2019); Maillet et al. (2018), for null or opposing findings). It is also in line with other experience-sampling research suggesting older adults’ thoughts are more present-focused (Jackson and Balota (2012); Maillet et al. (2019), although see: Giambra (1989); Maillet et al. (2018), for null or opposing findings) and pleasant (Maillet et al., 2018) in nature.

Certain dimensions of ongoing thought vary with age

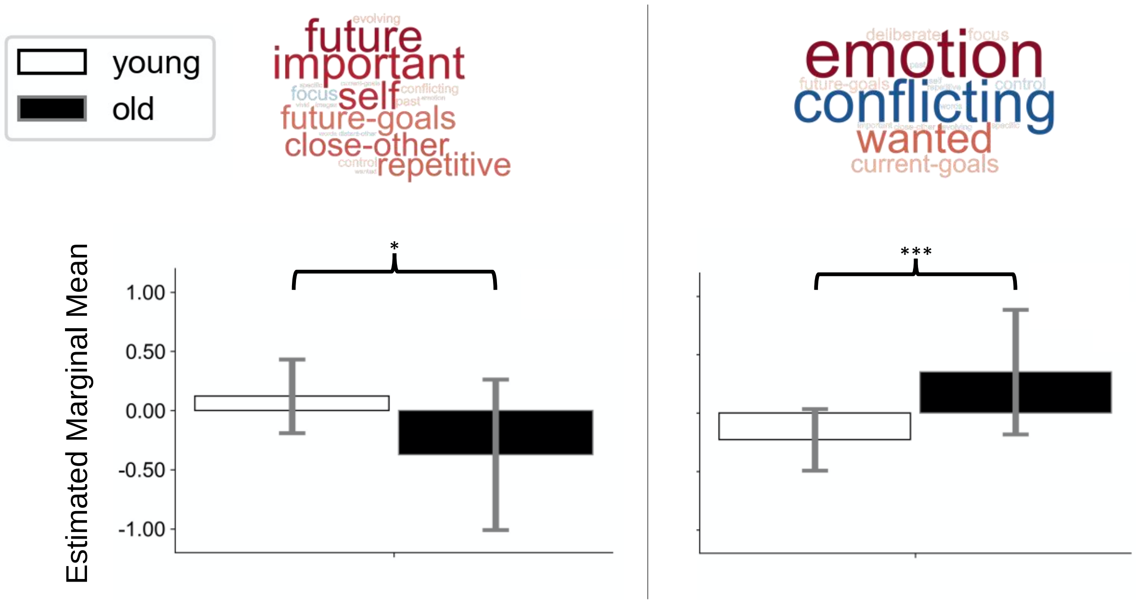

Figure 4. Linear mixed effects models for off-task thoughts about the future-self and positive, wanted thoughts showed significant effects of age. Plotting the estimated marginal means for these effects showed opposing relationships to age: off-task thoughts about the future-self were less prevalent in older adults, whereas positive, wanted thoughts were more prevalent.

Dimensions of ongoing thought show age-specific effects

Does the effect of context on components of thought differ for older vs. younger adults?

To understand whether the relationship between task demands and thought varied by age, we modelled age*context interactions. There were significant age and context interaction effects for component 1 (β = -.20, SE = .09, t(109) = -2.30, p = .023, 95%CI[-0.37, -0.03]) and component3 (β = -.20, SE = .07, t(125) = -2.71, p = .008, 95%CI[-0.35, -0.05]), suggesting that age group moderates the effect of context on components of thought. To interpret these interactions, we plotted the estimated marginal means for each thought component by age group according to easy, medium, and hard levels of context (see Figure 5). We also ran post-hoc tests in older and younger adults separately. Context was a significant positive predictor of component 1 in younger adults (β = .35, SE = .04, $t(57)$ = 9.78, $p < .001$, 95%CI[0.28, 0.42]) and older adults, but the effect was greater older adults (β = .55, SE = .07, $t(31)$ = 7.80, $p < .001$, 95%CI[0.41, 0.70]). For component 1 (deliberate, external goal-directed thought), for both younger and older adults show a positive relationship with context, but the slope is steeper for older adults, suggesting they increase this type of thinking more in response to increasing demands compared to younger adults. Context was a significant negative predictor of component 3 in younger adults (β = -.16, SE = .03, $t(50)$ = -5.44, $p < .001$, 95%CI[-0.21, -0.10]) but not in older adults (β = .05, SE = .07, $t(30)$ = .74, p = .464, 95%CI[-0.01, 0.18]). For component 3 (engaged in positive, present, goal-pursuit), older adults display higher levels of this kind of thinking overall and this increases slightly, but not significantly, as contextual demands increases. Younger adults do less of this kind of thinking and it decreases as contextual demands increase (i.e., the opposite pattern to older adults).

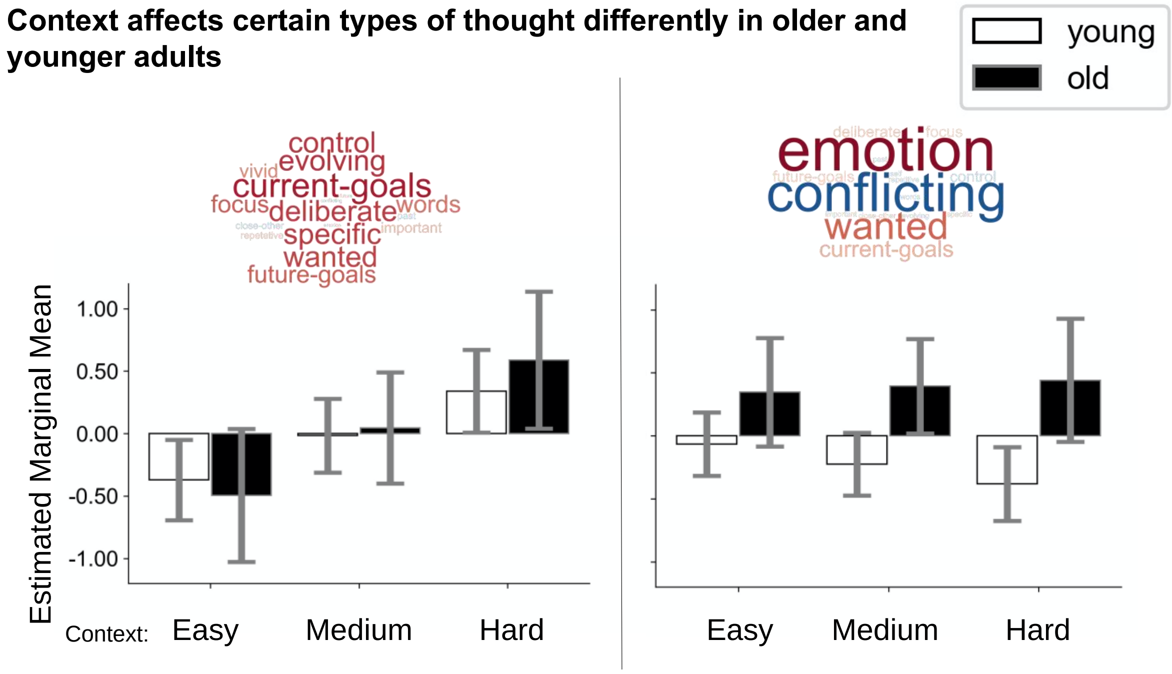

Figure 5. Linear mixed effects models for deliberate thoughts about current task goals and positive, wanted thoughts showed age by context interactions. Plotting estimated marginal means showed that, while deliberate thoughts about the external task increased with more demanding contexts in both age groups, this effect was more pronounced in older adults. In older adults, positive, wanted thoughts were not affected by context, but in younger adults these thoughts decreased as tasks got more challenging.

Does the relationship between cognition and components of thought differ between younger and older adults?

To examine whether the relationship between laboratory measures of fluid intelligence and memory, and thought components differed between older and younger adults, we examined age*cognition (fluid intelligence, semantic, and episodic memory) interactions. Only component 5 showed a significant interaction effect between age group and episodic memory (β = .34, SE = .14, t(96)= 2.45, p = .016, 95%CI[0.07, 0.62]). Plotting estimated marginal means showed that for younger adults, the relationship between episodic memory performance and past related thought was positive (e.g., higher scores on episodic memory predicted higher component scores on past-related thought); for older adults, this relationship was reversed compared to younger adults (see Figure 6). Post-hoc tests in older and younger adults separately confirmed a significant positive relationship in younger adults (β = .16, SE = .07, t(64) = 2.19, p = .032, 95%CI[0.01, 0.31]). The relationship between episodic memory and component 5 thinking was negative but this did not reach significance (β = -.17, SE = .12, t(33) = -1.45, p = .156, 95%CI[-0.40, 0.07]). Please note that our comparison between aggregated and trial level PCAs suggests that Component 5 was the most different dependent on the method used, in addition to showing the lowest explained variance among the components. Accordingly, this result should be treated with additional caution.

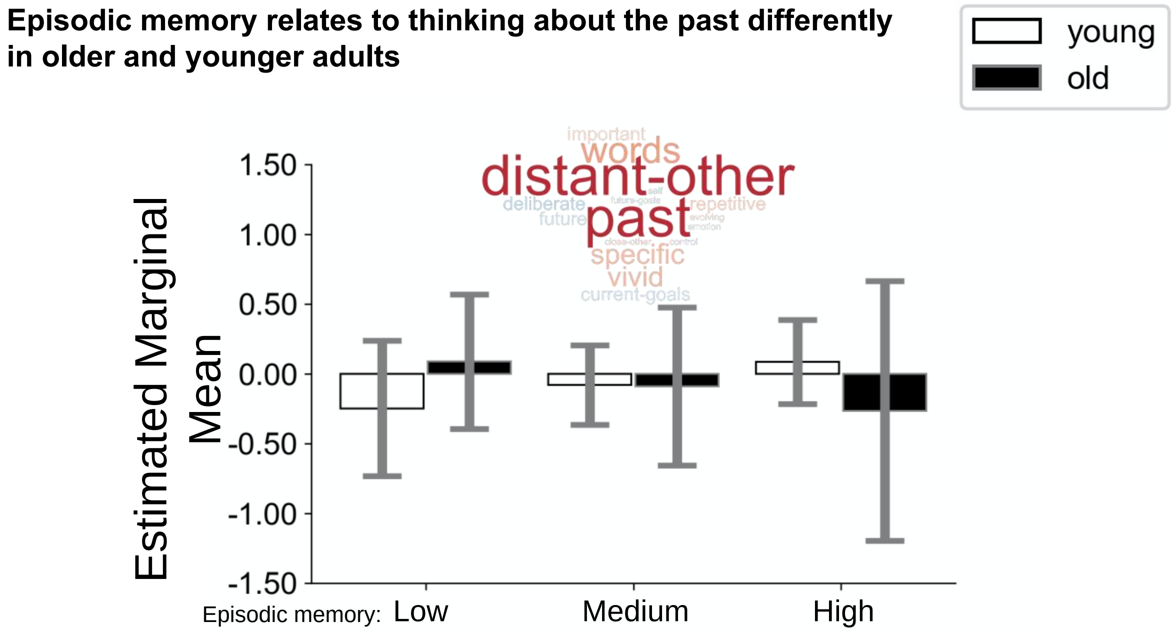

Figure 6. Linear mixed effects models for thinking about the past showed an age by episodic memory interaction. Plotting estimated marginal means showed that past related thought was negatively related to episodic memory in older adults, such that older adults with the poorest episodic memory thought the most about the past, although this relationship was not significant. Conversely, in younger adults, those with higher episodic memory thought significantly more about the past.

Discussion

Our study set out to apply multi-dimensional experience sampling to understand age-related changes in ongoing thought patterns in daily life and to understand how these reflect changes in cognitive traits and the external context. Importantly, our analyses found that components identified in both age groups separately were highly similar to those calculated using the whole sample. This result suggests that the structure of ongoing thought is similar in older and younger adults, helping to demonstrate the reliability of using MDES combined with dimensionality reduction approaches to study aging ongoing thought. While the structure of ongoing thought was similar in older and younger adults, we found that there are general differences in the types of thoughts that individuals who are younger and older tend to report in daily life. Younger individuals tend to engage in patterns of ongoing thought that are directed towards important personally relevant future goals disconnected from the here-and-now, in line with other studies (Irish et al., 2019; Jordão et al., 2019; Maillet et al., 2018; Seli et al., 2017; Seli et al., 2020), while older individuals tended to have ongoing thought patterns associated with pleasant states (Maillet et al., 2018; Mather, 2012) that feel wanted and do not conflict with current goals. In the latter case, this difference was most pronounced in situations with maximum demands, where this type of thought was most strongly reduced in younger participants. This difference in the general types of thinking shown by younger and older individuals may reflect the different points in their lives these two groups of individuals find themselves (Carstensen, Fung, & Charles, 2003). The youngest participants were all approximately university age participants for whom the immediate future contains many important life challenges and our experience sampling analysis is consistent with the view that they devote substantial portions of their ongoing thought to the consideration of these goals. Notably, while our study did identify a pattern of past-related thought, this was not the most dominant pattern of experience that old people engaged in (Irish et al., 2019). Instead, they tend to describe patterns of experience that were generally positive, lacked conflict with other goals, and tended to be loosely task focused. This may reflect the greater free time that older individuals have that allow them to engage in tasks and other social activities that they enjoy (Marcum, 2013), and may relate to reduced daily life concerns (McVay et al., 2013) that conflict with engaging wholly and enjoyably in specific tasks (Jordano & Touron, 2017). These results are also in line with evidence that older adults are more mindful than their younger peers (Fountain-Zaragoza, Puccetti, Whitmoyer, & Prakash, 2018), as this component of thought corresponds broadly to the definition of mindfulness as a construct. Future analyses accessing the quality, rather than just the difficulty, of older adults' daily life activities will be important in understanding the role lifestyle changes play in age-related differences in ongoing thought.

We also found important differences in how ongoing thought patterns vary with the degree of challenge imposed by the task in hand. Both older and younger individuals tended to show increasing focus on the task in hand as the degree of challenge increased; however, this tendency was stronger in older individuals. The ability to increase patterns of task focus in response to increasing task demands is referred to as context regulation (Smallwood & Schooler, 2015) and our study suggests that in general this process may be intact in both older and younger individuals. This contradicts some findings in laboratory studies that have found a reduction of context regulation in older adults (Martinon et al., 2019; McVay et al., 2013), but is in line with findings from Moran et al. (2021) that showed that task demands did not affect age-related differences in mind wandering in the laboratory. It is possible that these findings may be driven by the overall increased difficulty of laboratory tasks for older adults (supported by the fact that the differences are reduced in tasks older adults find easier; McVay et al. (2013)), or a more general problem in mapping laboratory based measures of performance to ongoing thought in the real world (Ho et al., 2020; McVay & Kane, 2012a). However, our study also suggests that there may be important differences in how external factors map onto the complex landscape of ongoing thought as we age. While older individuals show no differences in their ability to increase task focus when the environment becomes more challenging, they show less flexibility in other experiential domains. One possibility is that aging is associated with changes in how individuals regulate experience because they have learnt new strategies to perform tasks (Mata, Schooler, & Rieskamp, 2007). It is possible, for example, that older individuals use less demanding strategies for emotional regulation that allow them to maintain positive emotional states across all levels of environmental demand (Mather, 2012).

From this study it is unclear to what extent cognitive aging in memory and executive function is responsible for age-related changes in ongoing thought, but our results highlight that these relationships may not be as straightforward as current theories suggest (e.g., that reductions in cognitive resources (Maillet & Schacter, 2016) lead to reduced mind wandering). In younger adults it has been shown that individual differences in executive functions explain the extent to which different types of thought are engaged (Baird et al., 2012; Kane et al., 2007; Robison et al., 2020; H.-T. Wang, Bzdok, et al., 2018; H.-T. Wang et al., 2020; H.-T. Wang, Poerio, et al., 2018), and that this often depends on the situation in which thoughts arise (Levinson et al., 2012; Robison et al., 2020; Rummel & Boywitt, 2014; Turnbull, Wang, Schooler, et al., 2019). In our study we measured fluid intelligence using Raven's matrices and found that accuracy correlated positively with task focus (replicating prior studies linking executive control to on-task thoughts: (Kane et al., 2007; Levinson et al., 2012; McVay & Kane, 2012a, 2012b; McVay, Kane, & Kwapil, 2009; Mrazek et al., 2012; Rummel & Boywitt, 2014)) across both age groups. This finding seems to suggest that it is unlikely that aging executive functions are responsible for reductions in mind wandering, which is in line with null findings from Moran et al. (2021). While there were no differences in how fluid intelligence related to ongoing thought between older and younger adults, episodic memory did show age-specific effects, although this result involving the least stable component of thought identified in our analysis should be interpreted with additional caution. These results suggest that clarifying how cognitive aging relates to changes in ongoing thought will require extensive sampling of both multiple dimensions of ongoing thought content and the external context, as well as modelling interactions between these factors.

Limitations

There are several limitations to this study that need to be kept in mind when considering the findings. First, while this study provides evidence that ongoing thought reflects differences in cognition measured in the laboratory, no strong claims can be drawn about the precise role of cognitive decline in age-related changes in ongoing thought. This is due to the limited nature in which cognition was assessed. We included a single measure of fluid intelligence that has shown links to ongoing thought in other studies (Turnbull, Wang, Schooler, et al., 2019) and measures of external and internal details during an interview. It is unclear from this study the role that decline in specific components of executive functions and memory play in age-related changes in ongoing thought. Future studies using a more extensive battery of measures that have shown links to ongoing thought, including working memory capacity (Kane et al., 2007), attention (Robison et al., 2020), inhibition and task-switching (Kam & Handy, 2014; Turnbull, Wang, Schooler, et al., 2019), as well as measures of both memory performance (H.-T. Wang et al., 2020) and fluency, will be needed to clearly establish the precision with which ongoing thought dimensions measured in the real-world reflect individual differences in cognitive decline. This is especially true given that recent studies suggest that the original interpretation of external details from the AI as representing semantic memory may be inaccurate, and that these details may be a combination of episodic, semantic, and tangential details (Renoult et al., 2020; Strikwerda-Brown et al., 2019). For these reasons, we caution that the results of our exploratory study are preliminary and will require replication before any clear theoretical claims can be made about how cognitive aging in specific processes relates to age-related differences in ongoing thought. The main significance of our findings is highlighting that these relationships are complex and require an appreciation of the context-dependent nature of ongoing thought and its relationships to cognition.

Second, as some older adults did not have phones, they had to provide their thought reports on paper. This highlights a challenge of experience sampling in older adults, as matching experimental procedure across age groups is challenging and carries advantages as well as disadvantages. Using paper in this way provides a means of ensuring older adults are completing the reports in a way that they may be more comfortable with, particularly as it was specific to those who did not own smartphones and may be less literate with electronic devices. On the other hand, it may introduce differences related to the different methodologies. To further investigate this, we also performed PCAs separately in participants who completed the paper and smartphone versions, and compared the final scores with the original PCA with all participants combined. The high degree of similarity between the final scores (see Supplementary Figure 1) suggests that the difference in methods did not have a major impact on the degree to which participants reported engaging in specific dimensions of thought. This is an important finding; it suggests that using different approaches to measure ongoing thought may produce consistent findings in older adults. However, a more thorough assessment of the impact of different data collection approaches for self-reported ongoing thought in daily life will be needed before this technique can be rigorously applied to aging research, particularly given the fact that many older adults do not own a smartphone (Anderson & Perrin, 2017), and if they do they often show reduced technological literacy compared to their younger peers (S. Wang et al., 2019).

Additionally, older and younger adults were taken from different populations. As older adults were recruited from the community and younger adults from the University of York, there was likely greater variance in older adults both in terms of age and life circumstances. Older adults were also from a larger age range and included younger individuals than is typical in studies of aging. Future studies including a broader range of age groups will be needed to clarify whether there is more specific age-related variation within the range of our older age group (55-87 years old). As several studies have shown age-related changes in thought to differ between young-old and old-old adults (Giambra, 1989; Zavagnin et al., 2014), there may be more precise trajectories of change in both ongoing thought and underlying cognitive processes that we are missing in this study. Future research aiming to understanding the role of age and lifestyle factors more precisely will be necessary to determine exactly how and why ongoing thought changes with age. Future research should also include measures that are known to affect cognition, including years of education. As we did not include a measure of education, it is possible that our results could be affected by differences in the education level of older and younger participants. Including a measure of fluid intelligence likely captures some of the variance associated with education, but does not fully account for potential effects. While the younger adult population is likely to be relatively consistent in their education, as they were sampled from the student population, older adults likely showed greater variance in their education levels. Future studies either controlling for, or matching on, education level will be needed to assess how these factors affect age-related differences in ongoing thought. Relatedly, using cross-sectional research it is difficult to understand whether these findings represent true age-related changes or cohort effects. Studies have shown that differences seen in empathy (Grühn, Rebucal, Diehl, Lumley, & Labouvie-Vief, 2008) and ongoing thought (Giambra, 1989) measured using experience sampling are differentially affected by cohort and longitudinal processes. Longitudinal studies, or those comparing across older adults showing varying degrees of cognitive aging, will be needed before it can be established exactly how self-reported ongoing thought reflects cognitive aging.

Finally, an outstanding methodological question from this study concerns the extent to which different individuals contribute to the final thought components for reasons such as having different numbers of probes per person. In our study we used Linear Mixed Effects modelling and focused on the relationships to variables of interest (e.g., age or task performance) to identify meaningful individual differences in the thought components. Nonetheless, it is possible that certain features of the components themselves are disproportionately influenced by certain individuals, particularly those with more probes. PCA has been used on repeated measures data in other fields (Bradlow, 2002) to better understand the structure of repeated measures data. Furthermore, this approach has been used in many studies yielding reproducible patterns of thought across different data sets (for an empirical demonstration see: Smallwood et al. (2016); for an integrative review see: (Smallwood et al., 2021)). However, how repeated measures data with varying numbers of observations across participants affects the final component structure is an outstanding issue. To attempt to assess this, we compared the original PCA results with those obtained using averaged thought responses (giving one independent observation per person). The first four components showed high correspondence, but the fifth component was less strongly correlated across these analyses. This suggests that component 5 may be more influenced by certain individuals, potentially due to them answering more probes or answering more consistently high on specific questions. This component explained the least variance in the original analysis, and thus it is also likely to be the least stable component when calculated using aggregated data since this has far fewer observations and lower power. Nonetheless, the relationship between patterns of past-related thought and episodic memory should be treated with caution in the absence of further evidence supporting this association. While beyond the scope of this article, it would be worthwhile for future studies to compare PCA with more advanced multi-level dimensionality reduction techniques (Lovaglio & Vittadini, 2013) to provide additional clarity on how best to benefit from the enhanced statistical power gained by the application of decomposition techniques to trial level data.

Finally, recent studies have shown that more reliable indicators of the so-called mind-wandering state can be derived from the use of probes of the content of experience (Kane, Smeekens, Meier, Welhaf, & Phillips, 2020) rather than those asking about thought intention or depth. While our study included measured that would be defined as content (asking about thinking in images or words, or about the temporal orientation of thought, for example), we also asked questions that could be considered as asking about intention (e.g., were your thoughts deliberate or wanted), and measured the depth of thoughts using a scale. The individual differences in the confidence with which participants answer these questions may cause them to be less reliable than those asking about content (Kane et al., 2020). It is possible that important age-related changes in our ability to control ongoing thought patterns may be more apparent by a greater use of content thought probes in future studies. Relatedly, the ways in which different questions are interpreted by older and younger adults requires a more thorough evaluation. Research suggests that age-related differences in mind wandering are reduced by including questions asking about “task-related interference” separately (McVay et al., 2013). This suggests there may be differences in the way older and younger participants are interpreting “on-task” thoughts, as well as potentially other dimensions of ongoing thought.

Conclusion

We set out to describe the differences in the types of ongoing thought that younger and older adults engaged in during a week in their daily lives, and to understand whether these related to differences in cognition measured in the laboratory. We found that older and younger adults showed differences in the types of thoughts they routinely reported, predominantly driven by an increase in thoughts about the future-self unrelated to the here-and-now in younger adults, and an increase in positive, goal-pursuit in older adults. These findings replicate others showing a reduction in “mind wandering” type experiences in older adults (Jordão et al., 2019; Maillet et al., 2018; Seli et al., 2017; Seli et al., 2020), as well as an increase in positive thinking (Maillet et al., 2018), and add to the complex literature on the varied differences in ongoing thought content between older and younger adults (Giambra, 1989; Jackson & Balota, 2012; Maillet & Schacter, 2016). Our finding that thoughts about the future-self unrelated to the here-and-now related to reduced executive function replicated previous findings (Kane et al., 2007). We found that certain types of thought vary depending on the demands of the external context, and that these relationships vary in older and younger adults, further demonstrating the need to take contextual demands into account when attempting to understand differences in ongoing thought (Smallwood & Schooler, 2015). Finally, we found that the number of internal and external details participants reported during the AI related to the types of thoughts that older and younger adults engaged in as they moved between tasks with different demands. This provides a foundation for the idea that measures of ongoing thought may be able to detect individual differences in cognitive decline when measured in a context-dependent framework.

Competing interests

The authors declare no competing interests.

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