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Individual differences and 11-year longitudinal changes in older adults' prospective memory: A comparison with episodic memory, working memory, processing speed, and verbal knowledge☆

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ABSTRACT

Prospective Memory (PM; remembering intended actions after a delay) represents a core ability contributing to everyday functioning and independence in older adulthood. Despite its high relevance for successful aging, the understanding of individual differences in level and within-person change of PM in older adulthood is currently limited. Using longitudinal data from initially 364 older adults (between 65 and 80 years of age at wave 1; 46 % female) across four waves of the Zurich Longitudinal Study on Cognitive Aging, we examined (a) individual differences and (b) longitudinal change in PM performance over up to 11 years, (c) compared differences and change in PM with other central variables of cognitive functioning (episodic memory, working memory, processing speed, verbal knowledge), and (d) explored the effect of key sociodemographic variables (education, income, sex, health) on PM. Linear mixed modeling with Bayesian estimation indicated substantial individual differences in cognitive performance, with by far the highest variability in PM. Longitudinal age-related decreases were largest for working memory and cognitive speed, relatively small for PM, while verbal knowledge remained stable. Individual differences in age-related changes in performance were only observed for processing speed and verbal knowledge, but not for PM. This pattern remained after considering various cognitive and sociodemographic covariates. This is the first longitudinal study of PM that allows an in-depth examination of individual differences in both level and change in PM with comparison to other key cognitive abilities across older adulthood. The findings highlight the complex interplay between cognitive abilities, individual differences, and development across older adulthood, with implications for understanding cognitive aging.

Introduction

Prospective memory (PM)—remembering to perform planned intentions after a delay in the future (Zuber, Scarampi, Laera, & Kliegel, 2024)—is a key cognitive ability for younger and older adults. Everyday examples of PM are remembering to stop at the supermarket on the way home (event-based PM) or taking a meal out of the oven after 15 min (time-based PM). In older adulthood, individual differences in PM abilities have been associated with important health-related outcomes, cognitive decline, onset of dementia, and being able to live independently (e.g., Browning et al., 2023; Hering, Kliegel, Rendell, Craik, & Rose, 2018; Kozuki et al., 2023; Laera et al., 2023a). Due to its central role in cognitive and everyday functioning in older adulthood, understanding individual and age-related differences in PM abilities has been a core interest of PM research from its inception (e.g., Einstein, McDaniel, & Herrmann, 1996) through recent years (e.g., Laera et al., 2023b). The majority of studies report a negative relationship between age and PM performance, particularly when PM is assessed in complex

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laboratory settings (for *meta*-analyses and overviews, see Henry, MacLeod, Phillips, & Crawford, 2004; Horn & Freund, 2021; Ihle, Hering, Mahy, Bisiacchi, & Kliegel, 2013, Kliegel, Jäger, & Phillips, 2008; Kliegel et al., 2016; Laera et al., 2023b; Zuber & Kliegel, 2020). Yet, compared to other cognitive abilities that are crucial in older adulthood and have been studied more extensively—such as episodic memory, working memory, processing speed, or verbal knowledge—our understanding of individual differences in both mean level and within-person change of PM in older adulthood is still limited.

On the one hand, this might be due to the fact that the literature on PM and aging has mostly focused on *young-old* adults (typically younger than 75 years). Only a few studies so far have included samples that cover a larger age range in older adulthood (for an overview, see Bayen, Rummel, Ballhausen, & Kliegel, 2024). Interestingly, the few PM studies that included both young-old and old-old adults suggest that negative age-effects may further increase within old age and that individual differences may be even larger in old-old compared to young-old adults (Henry et al., 2015; Ihle et al., 2019; Kvavilashvili et al., 2009, 2013; Zuber, Ihle, Blum, Desrichard, & Kliegel, 2019a). Similarly, extensive research on other cognitive abilities has highlighted the importance of studying age-effects into very old age in order to accurately reflect individual trajectories of cognitive functioning (e.g., Baltes & Smith, 1997; Baltes, Lindenberger, & Staudinger, 2006; Salthouse, 2009; Schaie, 1994). As studies with old-old adults are largely lacking in PM research, it seems particularly important to examine individual differences in PM abilities across the entire range of older adulthood by studying performance of not only young- and middle-old but also old-old adults.

On the other hand, our understanding of individual differences in within-person change of PM is limited because the vast majority of studies have addressed age differences with cross-sectional designs (by comparing PM performance of younger and older adults from different cohorts), rather than studying individual developmental trajectories across time. We are only aware of two longitudinal studies that provide information on how PM performance changes across older adulthood in community-dwelling, healthy older adults: Sullivan et al. (2022) assessed two PM tasks in 271 older adults (mean age 67.5 years) at baseline and across three follow-ups spread over 7 years. To assess PM, participants completed the Memory for Intentions Screening Test (MIST; Raskin, Buckheit, & Sherrod, 2010; Woods et al., 2008), during which they performed word search puzzles as ongoing tasks while having to remember to perform the PM tasks. Specifically, for the event-based PM task, older adults had to interrupt the ongoing task and perform an intended action when encountering predefined cues (e.g., when they were shown a red pen, they had to sign their name on the paper). For the time-based task, participants had to remember intended actions after a predefined time had elapsed (e.g., reminding the experimenter that it is time to take a break after 15 min). Sullivan et al. reported a small but significant age-related decrease for event-based PM, whereas time-based PM did not change with age. Further findings have been reported by Kamberis, Cavuoto, and Pike (2021), who also assessed two PM tasks in older adults at baseline (aged 70 years and older; $N = 181$) and after five years ($N = 99$). As an event-based PM task, older adults had to remember to request an envelope at the end of the experiment. As a more naturalistic PM task, participants had to remember to press a button on their Actiwatch when going to bed and when waking up. The authors found a negative association between age and event-based PM, whereas naturalistic PM only decreased in a subgroup of participants with high subjective memory decline (i.e., in those participants who reported that their memory deteriorated since college).

Although both studies provide relevant first insights into potential age-related changes of PM, they also have methodological limitations (e.g., regarding the number of measurement occasions and the covered time span). Kamberis et al. included only a single follow-up assessment that was conducted five years after baseline. The study of Sullivan et al. spanned across 7.1 years at maximum and included four measurement points. However, the majority of participants were only retained until the first follow-up after 2.4 years ($N = 137$; 51 % of the original sample), whereas there were pronounced dropouts in the second follow-up (remaining $N = 47$; 17 % of original sample), and the final sample (third follow-up) included less than 5 % of the original sample ($N = 12$). Thus, both studies presented findings from relatively small samples, particularly at the final assessment. Sample size and number of measurement occasions can have important methodological implications. For example, research on other cognitive abilities shows that practice effects may often occur in longitudinal studies that are based on few measurements and therefore can bias results, again highlighting the relevance of studying longitudinal trajectories across many measurement times in large samples (e.g., Brandmaier, von Oertzen, Ghisletta, Lindenberger, & Hertzog, 2018; Ghisletta et al., 2020; Hertzog, 1985; Hertzog, Lindenberger, Ghisletta, & Oertzen, 2006; Salthouse, 2010).

Together, these constraints have limited the potential to fully explore individual differences in PM performance in and across old age and thereby only provide limited evidence on the long-term change of PM in late life. Moreover, alongside examining individual differences in both the level and within-person changes of PM in older adulthood, it is crucial to consider PM development in comparison to other core cognitive abilities. This can contribute to a deeper understanding of the complex interplay among various cognitive abilities, highlighting the multidimensionality of cognitive development in aging.

Individual differences and changes across older adulthood have been studied more extensively for other cognitive abilities that are also central for cognitive functioning, such as episodic memory, working memory, processing speed, and verbal knowledge. It is beyond the scope of the present article to review the most recent advancements in these areas of research, but this literature consistently shows that although performance in many cognitive tasks declines across adulthood, there are important differences between domains of cognitive functioning: age-related decline in fluid cognitive abilities (e.g., processing speed and working memory) tends to be much larger than in crystallized cognitive abilities (e.g., verbal and semantic knowledge). Moreover, there is substantial variability in how well individuals perform at any specific age (i.e., there are individual differences in level of performance) as well as in how their performance changes over time (i.e., individual differences in within-person change; e.g., Baltes & Mayer, 1999; Ghisletta, McArdle, & Lindenberger, 2006; Ghisletta, Rabbitt, Lunn, & Lindenberger, 2012; Ghisletta, Dahle, & Raz, 2023; Hertzog, 2017; Horn & Cattell, 1967; Hultsch, MacDonald, & Dixon, 2002; Li et al., 2004; Lindenberger & Ghisletta, 2009; Lövdén, Fratiglioni, Glymour, Lindenberger, & Tucker-Drob, 2020; Robitaille, Muniz, Piccinin, Johansson, & Hofer, 2012; Rönnlund, Nyberg, Bäckman, & Nilsson, 2005; Park et al., 2002; Park & Festini, 2017; Salthouse, 2000; 2004; 2009; 2017; Schaie, 1994; Tucker-Drob, Brandmaier, & Lindenberger, 2019).

Although further cognitive abilities (e.g., episodic memory, working memory, and processing speed) have either been shown to contribute to or correlate with PM performance (e.g., Salthouse, Berish, & Siedlecki, 2004; Uttl, White, Cnudde, & Grant, 2018; Zeintl, Kliegel, & Hofer, 2007; Zuber, Kliegel, & Ihle, 2016), we currently know very little about whether individual differences in PM are similar compared to these abilities and whether age differences in PM persist beyond controlling for performance in these abilities. Moreover, it seems important to identify further person variables that explain individual variability in PM performance (e.g., for diagnoses and predictions). According to studies focusing on the other core cognitive abilities, variables that are often associated with cognitive performance include sociodemographic variables and aspects of physical health. However, the role of these variables for PM needs to be investigated more closely.

One main sociodemographic variable that has been shown to consistently predict cognitive functioning in late life is *education*, with higher levels of education being associated to higher levels of cognitive performance, slower decline, and less variability across cognitive domains in old age (e.g., Christensen et al., 1999; Lövdén et al., 2020; Opdebeeck, Martyr, & Clare, 2016; Stern, 2002; Tucker-Drob &

Salthouse, 2011). Relatedly, higher *socioeconomic status* has repeatedly been associated with better cognitive performance in older adulthood (but not necessarily linked to cognitive change) so that old-old adults with higher socioeconomic status may display similar cognitive performance as 10-years-younger adults with lower socioeconomic status (De Looze et al., 2023; Karlamangla et al., 2009; Ruiz, Hu, Martikainen, & Bobak, 2023; Wang, Bakulski, Paulson, Albin, & Park, 2023). Further, better *overall physical health* (e.g., reporting better health or less symptoms of illness, being physically more active, higher muscular strength, better respiratory functioning, faster walking speed) has been associated with better cognitive performance in old age, smaller cognitive decline, and less variability in performance (e.g., Chistensen et al., 1999; Colcombe & Kramer, 2003; Ritchie et al., 2016; Wang et al., 2023). Although the role of *biological sex* has frequently been studied in older adulthood, findings regarding the direction of its effect are inconsistent, with some studies suggesting that women show stronger decline and display more variability across cognitive domains than men (e.g., Christensen et al., 1999; Karlamangla et al., 2009), others suggesting stinger decline in men (e.g., Ritchie et al., 2016), and yet others finding no association between sex and cognitive decline (e.g., Barnes et al., 2003).

Although these sociodemographic variables have been extensively studied in the context of understanding performance and decline in many core cognitive abilities, their effect on PM has been nearly neglected. The PM-aging literature has more often focused on how task-inherent variables (such as task setting, type, or demands) and person-inherent variables (such as cognitive abilities or motivation) contribute to age-effects. Some of the available studies that included these sociodemographic variables hint toward better education being linked to better PM performance (e.g., Chan, Qing, Wu, & Shum, 2010; Fine et al., 2019; Huppert, Johnson, & Nickson, 2000; Simard et al., 2019; Zhou et al., 2013), whereas others do not find a significant link of education to PM (e.g., Au, Vandermorris, Rendell, Craik, & Troyer, 2018; Cadavid, Camuy, Velez, & Raskin, 2023; Palermo et al., 2020). So far, only one study explored the life course mechanisms of socioeconomic conditions and PM and found that higher socioeconomic status in middle adulthood (but not in childhood nor in older adulthood) predicted better PM in late life (e.g., Künzi et al., 2021). Although it has often been suggested that PM contributes to health and wellbeing in old age, inversely, whether general health relates to PM performance and PM development in old age has yet to be examined. Finally, regarding sex, although one study reported that being male was associated to more PM impairments in a single-item PM task for which participants had to remember to write their initials on the back of an envelope after reception (Huppert et al., 2000) the majority of studies did not find any significant effects or differences of sex (e.g., Au et al., 2018; Chan et al., 2010; Simard et al., 2019; Uttl et al., 2018). Overall, reviewing the previous literature shows that sociodemographic variables have been examined much less systematically in PM and it currently remains unclear whether these broader socioeconomic variables can also explain individual differences in PM, and in particular, whether they can contribute to or account for PM change in older adulthood beyond age per se – again, because longitudinal studies into very old age are largely lacking.

To sum up, the vast majority of the previous PM studies have examined age-effects and individual differences with cross-sectional designs comparing PM performance of younger and older adults, predominantly based on age-restricted samples that include no or only few old-old adults. Although two longitudinal studies provided first insights into potential trajectories of PM in old age (Kamberis et al., 2021; Sullivan et al., 2022), the currently available evidence on individual differences in longitudinal trajectories of PM remains scarce and is partially inconclusive, leaving important empirical questions open:

Although cross-sectional studies comparing younger and older adults repeatedly found that PM differs between age groups, first, individual differences in level of PM performance in older adulthood remain largely unexplored, and second, it is relatively unclear to which extent age-related changes in PM emerge when performance is measured longitudinally. Third, it remains unknown how PM develops in old age over longer periods of time (over more than a decade) and whether there are individual differences in within-person change of PM performance in older adulthood. Fourth, previous studies typically did not compare variability or developmental trajectories of PM to other core aspects of cognition, namely, episodic memory, working memory, processing speed, or verbal knowledge. It therefore has yet to be examined whether individual differences in PM across old age are similar or different in magnitude compared to other central cognitive functions. Fifth, in view of the previous scarcity in longitudinal PM research, it remains unknown whether episodic memory, working memory, processing speed, and verbal knowledge contribute to and potentially account for any age-effects in PM or whether age-effects persist beyond these core correlates. Finally, beyond these cognitive correlates, it remains to be explored whether individual differences in level and within-person change of PM can be explained by important predictors of individual differences, namely education, socioeconomic status, sex, and health. To investigate these questions, the present study set out to examine the magnitude of individual differences in developmental trajectories of PM and to compare them with those from episodic memory, working memory, processing speed, or verbal knowledge, using data from the Zurich Longitudinal Study on Cognitive Aging (see Zeintl et al., 2007; Zimprich et al., 2008).

Method

The data analyzed in the present article are from the Zurich Longitudinal Study on Cognitive Aging. This longitudinal study examines age-related changes in a broad set of cognitive tasks across older adulthood and includes many further demographic and socioeconomic variables (for a detailed project description, see Zeintl et al., 2007; Zimprich et al., 2008). The present analyses are based on all four waves currently available. Specifically, participants were assessed at T1 (initial baseline measurement occasion), at T2 after $M = 1.5$ years ($SD = 0.2$), at T3 after $M = 3.74$ years ($SD = 0.57$), and at T4 after $M = 5.58$ years (SD = .09). The time between the first and fourth measurement occasion was $M = 10.8$ years ($SD = 0.10$).

Participants and materials

Zimprich et al. (2008) provide a detailed description of the design, sample, recruitment procedure, pre-screening method, and selection criteria. The sample at T1 comprised 364 older adults aged between 65 and 80 years ($M = 72.98$, $SD = 4.43$), 46 % female. The average time invested in formal education was $M = 12.84$ years ($SD = 3.30$), with men having significantly longer education times ($M_{men} = 13.69$, $SD_{men} = 2.97$) than women ($M_{women} = 11.84$, $SD_{women} = 2.79$; $t(357.57) = 6.10$, $p < .001$)), which reflects typical sex inequalities in education among the studied cohorts in the broader Swiss population (e.g., Federal Statistical Office, 2024).

The sample comprised 335 older adults at T2 ($M_{age} = 74.43$, $SD = 4.41$; 46 % female), 236 older adults at T3 ($M_{age} = 77.90$, $SD = 4.42$, 45 % female), and 149 older adults at T4 between 76 and 91 years ($Mage = 83.05$, $SD = 4.37$, 44 % female). On average, participants were assessed on 2.98 measurement occasions ($SD = 0.96$) and remained in the study for $M = 6.70$ years ($SD = 3.92$).

Materials

For each cognitive task the scores are based on the number of correct responses and were divided by the number of presented items such that they can be interpreted as 'proportion correct' (range: 0–1). We then constructed composite scores for each cognitive domain with equal weighting of the corresponding subtasks (e.g., for PM: average of scores

from the pencil, background change, token tasks).

Prospective Memory Tasks. For all PM tasks, participants were instructed and subsequently asked to explain the task in their own words in order to verify that they correctly understood the instructions. If necessary, task instructions were repeated until the participants were able to repeat them correctly. Further, participants were informed that the PM cues of each task could appear during the entire assessment and that they would not be reminded of these tasks after the instruction phase. For all PM tasks, there was a delay between the instruction phase and the occurrence of the first PM cue.

Red pencil task. For this task, participants were instructed to immediately repeat the words "red pencil" whenever they were mentioned by the experimenter (Dobbs & Rule, 1987). In total, the experimenter used the words "red pencil" three times during the assessment (*red pencil* score: proportion of times correctly repeating the words "red pencil"). In the present sample, the Cronbach's alpha for this task was.86 (for further information about reliability measures of the current test battery, see also Zeintl et al., 2007; Zimprich et al., 2008).

Background change task. Modeled after the background pattern task (Park, Hertzog, Kidder, Morrell, & Mayhorn, 1997), participants had to remember to press a specific key on the keyboard whenever the background color of the computer screen changed to yellow, which occurred three times (*background change* score: proportion of times correctly pressing the designated key after the background changed to yellow). In the present sample, the Cronbach's alpha for this task was.58.

Token task. Participants were told that they would have to remember to take a token out of the drawer and place it on the experimenters desk every time the instructions of a new task started with the sentence "The next task involves digits.", which overall happened four times (*token* score: proportion of tokens placed on the desk). In the present sample, the Cronbach's alpha for this task was.84.

Episodic Memory Tasks. We used three standard tasks to measure episodic memory.

Story recall. The Logical Memory subtest of the German version of Wechsler Memory Scale-Revised (Härting et al., 2000) was administered. A short story of 66 words was read to the participants twice. Immediately after the second time, participants had to recall as many details as possible. In total, the story contained 23 key-elements (e.g., first and last name of the main character) and each element correctly recalled was accredited with 1 point. As per previous research, test–retest reliability of this task is.79 (Härting et al., 2000).

Picture memory. Participants were asked to name a sequence of twelve pictures (selected from the Nuremberg Age Inventory; Oswald & Fleischmann, 1999) which were consecutively presented on the computer screen at an interval of 2.75 s. After naming the last picture, participants were immediately asked to verbally recall as many of the twelve pictures as possible in any order. In the present sample, the Guttman split-half reliability was.47, and as per previous research test–retest reliability of this task is.67 (Oswald & Fleischmann, 1999).

Paired associates task. A modified version of the Verbal Paired Associates subtest of the German version of Wechsler Memory Scale-Revised (Härting et al., 2000) and the Munich Verbal Memory Test (Ilmberger, 1988) was administered. A sequence of twelve semantically unrelated word-pairs was presented on a computer screen at a pace of 4 s per pair. Participants were asked to read each pair aloud. After 1 s, the next pair appeared. After the last pair was presented, the experiment was paused for a few seconds. Next, the first word of one of the word-pairs was presented (e.g., "sky") and participants had 5 s to respond with the correct pair (i.e. "cloud"). In the present sample, the Cronbach's alpha for this task was.67. As per previous research, test–retest reliability in the Wechsler Memory Scale-Revised is.78 (Härting et al., 2000).

Processing Speed Tasks. We used three tasks to measure cognitive processing speed.

Number comparison. Participants were of number-pairs (e.g., 73845_73855) whose length randomly varied between 3 and 13 digits (Ekstrom, French, Harman, & Dermen, 1976). Participants had to judge whether the pair on the screen showed identical or non-identical numbers by pushing designated buttons on the keyboard. After hitting a response button, the next number-pair was presented. In total, participants had 90 s to perform this task. In the present sample, the Cronbach's alpha for this task was.81. As per previous research, test retest reliability is between.70 and .82 in young adult samples (Ekstrom et al., 1976).

Identical pictures. For each trial, participants were shown a row of six squares (aligned from left to right on the computer screen), each of which contained a shape (Ekstrom et al., 1976). The shape in the first square in the row (from left) was the target-shape and participants had to identify which of the remaining squares contained an identical shape by pressing designated buttons. After hitting a response button, the next row of squares was presented. In total, participants had 90 s to perform this task. In the present sample, the Cronbach's alpha for this task was.88. As per previous research test retest reliability is.87 for males and.81 for females (Ekstrom et al., 1976).

Digit-letter substitution. For each trial, a lookup table was shown on the top of the screen which indicated five digit-letter pairs (e.g., 2_e). At the center of the screen, one of the five letters from the lookup table was depicted, and participants had to indicate the associated digit as fast as possible by pressing the number-key on the keyboard. After hitting a key, the next lookup table and target letter were presented. In total, participants had 90 s to perform this task. In the present sample, the Cronbach's alpha for this task was.93. As per previous research with a similar task, test–retest reliability is.88 (Houx et al., 2002).

Working Memory Tasks. We used three working memory tasks.

Operation span task. Short sequences of simple arithmetic problems followed by a question mark were presented on the computer screen one at a time (i.e. 9 / 3 = 4?) and participants had to indicate whether the result was correct or incorrect by pressing designated keys on the keyboard (Turner & Engle, 1989). In addition, participants had to read aloud and memorize the last digit of each equation (i.e. 4). The sequence length could vary between two and five arithmetic problems, after which participants had to recall the memorized digits in their original order. In total, there were eight sequences, with the same number of "short" and "long" sequences for all participants. A sequence was scored as "correct" when all digits of the sequence were correctly recalled. In the present sample, the Cronbach's alpha for this task was.80. As per previous research, test–retest reliability is.73 to.81 (Klein & Fiss, 1999; Turley-Ames & Whitfield, 2003).

Reading span task. Sequences of unrelated, simple sentences (of seven to nine words) were presented on the computer screen one sentence at a time (Daneman & Carpenter, 1980). Participants were asked to read the sentences aloud and judge their coherence (whether they made sense or not) by pressing designated keys on the keyboard while memorizing the last word of each sentence. The sequence length could vary between two and five sentences, after which participants had to recall the memorized words in their original order. In total, there were eight sequences, with the same number of "short" and "long" sequences for all participants. A sequence was scored as "correct" when all digits of the sequence were correctly recalled. In the present sample, the Cronbach's alpha for this task was.71. As per previous research, test–retest reliability is.76 (Friedman & Miyake, 2004).

Counting span task. Sequences of displays depicting circles and squares were presented, and participants had to count aloud all targets (dark blue circles) among the distractors (dark blue squares and light blue circles) and enter the final count by pressing the corresponding number-key on the keyboard (Engle, Tuholski, Laughlin, & Conway, 1999). Each display had a varying number of targets (three to nine dark blue circles), shape distractors (one to five light blue circles) and color distractors (one, three, five, seven, or nine dark blue squares). The sequence length could vary between two and five displays, after which participants had to recall the memorized numbers in their original order (for each display, the correct answer was the number initially entered

and memorized by the participant, instead the actual number of targets displayed). In total, there were eight sequences, with the same number of "short" and "long" sequences for all participants. A sequence was scored as "correct" when all numbers of the sequence were correctly recalled. In the present sample, the Cronbach's alpha for this task was.68.

Verbal Knowledge Test. As an indicator of crystallized intelligence, we used a verbal knowledge vocabulary task. Specifically, participants had to identify one correct word presented among four nonwords in each trial that were similar in spelling or sound. In total, there were 37 trials selected from the German vocabulary test MWT (Spot-a-word intelligence test or "Mehrfachwahl-Wortschatz- Intelligenztest;" Lehrl, 1999). Each correctly identified word during a total duration of seven minutes was accredited with 1 point. In the present sample, the Cronbach's alpha for this task was.67.

Sociodemographic variables. Sociodemographic variables were assessed through self-reported questionnaires. Self-reported highest achieved education was categorized into three levels for the present analyses: Level 1 = no school/primary school/obligatory school, comprising $M = 8.57$ (ranging from 2 to 14) years of formal school education in the present sample; level 2 = vocational school/or middle school, comprising $M = 12.46$ (8 to 19) years of education; level 3 = higher technical school or university, comprising $M = 17.25$ (12 to 23) years of education. As indicator of socioeconomic status, we used participants' self-reported monthly gross income per household, which we categorized into four levels for the present analyses (level 1: less than 4000 CHF; level 2: 4000–6000 CHF; level 3: 6000–8000 CHF; level 4: more than 8000 CHF (exchange rate at T1: 1 CHF ~ 0.85 USD). Participants rated their general health on a scale from 1 to 6. Sex was coded as male = 0 and female = 1.

Procedure

Participants underwent individual testing with a trained researcher who remained present throughout the entire duration of the testing session. Participants could use their corrective glasses or hearing aids, if they had any. The testing environment was a quiet room, furnished with a conventional desk, computer, and chair. At the beginning of the study, participants were provided with an initial overview of the procedure. After signing the informed consent, they filled in a series of demographic and other questionnaires in paper–pencil format and then completed the cognitive test battery on a computer. The testing session lasted a total of two hours, with a short five-minute break after one hour. At each wave, conceptually similar parallel versions of the same tasks but consisting of different stimuli were administered. A more detailed description of procedure and tasks can be found in Zeintl et al. (2007) and Zimprich et al. (2008).

Results

Table 1 shows means and standard deviations of participants' performance on the outcome variables at the four measurement occasions (T_1 to T_4). The Supplementary Material S1 includes further information about zero-order Pearson correlations between all outcome variables at T_1. Supplementary Material S5 presents additional distributional information on individual performance and intraindividual variability across measurement occasions.

Visualizing age-related changes

To visually compare the age-related variability in PM, episodic memory, working memory, processing speed, and verbal knowledge, we plotted the individual performance trajectories across the test occasions of the Zurich Longitudinal Study on Cognitive Aging as a function of age (see Fig. 1). The age groups at T1 of young-old (65–70 years), middle-old (70–75 years), and old-old adults (75–80 years) are shown in different colors. As can be seen, there was substantial interindividual variability in all cognitive variables, and particularly for PM. Age-related longitudinal decreases appear to be most pronounced for cognitive speed and for working memory, whereas verbal knowledge appears to be relatively more stable within participants, consistent with previous results (e.g., Park et al., 2002).

Linear mixed modeling of age-related changes

To quantify and test variability, we next analyzed individual differences (a) in the level of performance and (b) in individual changes across the four measurement occasions with linear mixed models (LMMs). LMMs provide a powerful approach to account for the nested structure of longitudinal data, to disentangle between-person variability (level 2)

Table 1
Means and standard deviations of cognitive tasks performance across four measurement occasions (T_1 to T_4).

		Ms				*SDs*			
		T_1	T_2	T_3	T_4	T_1	T_2	T_3	T_4
Age (years)	Young-old	68	69	73	79	2	2	2	2
	Middle-old	73	74	78	84	2	2	2	2
	Old-old	78	79	83	89	1	1	1	2
Prospective Memory	Composite	.409	.514	.565	.491	.322	.297	.311	.300
	Background change	.415	.335	.429	.424	.438	.301	.290	.305
	Red pencil	.419	.592	.680	.610	.437	.439	.431	.432
	Token task	.393	.616	.586	.395	.398	.399	.428	.405
Episodic Memory	Composite	.483	.501	.486	.429	.122	.132	.137	.134
	Story recall	.631	.610	.587	.524	.179	.162	.166	.174
	Picture memory	.570	.607	.554	.535	.131	.134	.172	.178
	Paired associates	.250	.287	.291	.216	.196	.234	.253	.210
Working Memory	Composite	.622	.654	.650	.376	.149	.161	.200	.151
	Reading span	.594	.620	.620	.433	.168	.163	.238	.207
	Operation span	.629	.667	.642	.482	.214	.225	.273	.281
	Counting span	.644	.675	.653	.195	.175	.191	.239	.118
Processing Speed	Composite	.575	.528	.508	.468	.108	.110	.111	.121
	Digit-letter task	.637	.595	.573	.532	.133	.136	.133	.151
	Identical pictures	.648	.554	.524	.479	.138	.143	.143	.156
	Number comparison	.440	.435	.424	.392	.110	.109	.118	.101
Verbal Knowledge		.872	.869	.863	.858	.068	.076	.092	.091
Health		.536	.524	.528	.511	.090	.086	.090	.115

Note. Performance is scaled from 0 to 1 as proportion correct; *Ms* = Means; *SDs* = Standard Deviations; Composite = composite score used in the present analyses (calculated as mean over the three subtasks of each cognitive construct).

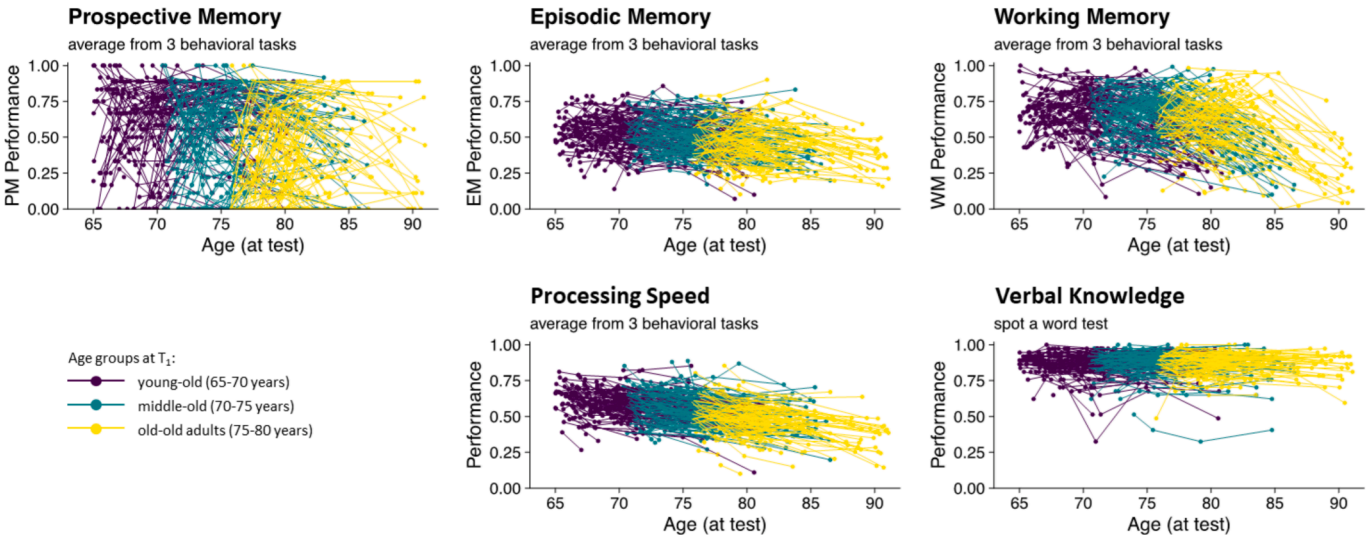

Fig. 1. Plots of individual longitudinal cognitive change over 11 years in the Zurich longitudinal study on cognitive aging. **Note.** In the Spaghetti plots, points connected with lines represent performance by individual participants in the study, who were tested repeatedly across maximally four measurement occasions; time between the first and fourth measurement occasion was: $M = 10.8$; $SD = 0.10$ years; all cognitive variables are scaled from 0 to 1 for ease of comparison. The age groups at T_1 of young-old (65–70 years), middle-old (70–75 years), and old-old adults (75–80 years) are shown in dark purple, turquoise, and yellow respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

from within-person changes (level 1), and to deal with missing observations (e.g., Curran & Bauer, 2011; McCormick, Byrne, Flournoy, Mills, & Pfeifer, 2023; Raudenbush & Bryk, 2002). Specifically, for the cognitive variables in this study (i.e., PM, episodic memory, working memory, processing speed, verbal knowledge), we estimated parameters from three different LMMs: In Model 1, we estimated a model with random intercepts only (but no predictors) to quantify the proportion of between-person variability to the total variability (i.e., intraclass correlation coefficient) in a dependent cognitive variable. In Model 2, we estimated a model with fixed effects (chronological age across test occasions) and random intercepts (to account for individual differences in level of performance).

In Model 3, we estimated a model with fixed effects (chronological age across test occasions), random intercepts, and additional random slopes (to additionally account for differences in intraindividual change across test occasions and for the possible correlation between the intercepts and the slopes).

In order to interpret the parameters from the best-fitting model, we

Table 2
Multilevel modeling results for prospective memory, episodic memory, working memory, processing speed, and verbal knowledge.

Effect/predictor variables		Dependent Variable Prospective Memory		Episodic Memory		Working Memory		Processing Speed		Verbal Knowledge	
		B	95 % CI	*B*	95 % CI	*B*	95 % CI	*B*	95 % CI	*B*	95 % CI
Random effects											
	SD (Intercept)	**0.20**	**[0.18, 0.22]**	**0.08**	**[0.07, 0.09]**	**0.11**	**[0.10, 0.13]**	**0.08**	**[0.07, 0.09]**	**0.06**	**[0.05, 0.06]**
	SD (Age)	—	—	—	—	—	—	**0.02**	**[0.01, 0.03]**	**0.01**	**[0.00, 0.01]**
Fixed effects											
	Intercept	**0.36**	**[0.20, 0.51]**	**0.46**	**[0.40, 0.52]**	**0.58**	**[0.49, 0.68]**	**0.51**	**[0.45, 0.57]**	**0.91**	**[0.87, 0.95]**
	Age	**−0.02**	**[-0.03, 0.00]**	**−0.04**	**[-0.04, −0.03]**	**−0.10**	**[-0.11, −0.08]**	**−0.07**	**[-0.07, −0.06]**	−0.00	[-0.01, 0.00]
	PM_{T1}	—	—	**0.02**	**[0.01, 0.03]**	0.00	[-0.01, 0.02]	0.00	[-0.01, 0.02]	0.00	[-0.00, 0.01]
	EM_{T1}	**0.08**	**[0.05, 0.11]**	—	—	**0.03**	**[0.01, 0.05]**	**0.01**	**[0.00, 0.03]**	**0.01**	**[0.01, 0.02]**
	WM_{T1}	**0.04**	**[0.01, 0.07]**	**0.02**	**[0.01, 0.03]**	—	—	**0.02**	**[0.01, 0.03]**	**0.02**	**[0.01, 0.02]**
	$Speed_{T1}$	**0.04**	**[0.01, 0.07]**	0.01	[-0.00, 0.02]	0.01	[-0.00, 0.03]	—	—	−0.00	[-0.01, 0.00]
	$Vocabulary_{T1}$	0.02	[-0.01, 0.05]	**0.02**	**[0.01, 0.03]**	**0.03**	**[0.01, 0.05]**	0.00	[-0.01, 0.02]	—	—
	Sex_{male}	**0.05**	**[0.02, 0.08]**	**−0.02**	**[-0.03, −0.01]**	0.01	[-0.01, 0.02]	−0.00	[-0.01, 0.01]	−0.00	[-0.01, 0.00]
	Health	0.21	[-0.08, 0.49]	0.04	[-0.08, 0.15]	0.01	[-0.16, 0.18]	0.03	[-0.08, 0.14]	**−0.08**	**[-0.16, −0.01]**
	$Education_{level1}$	−0.02	[-0.08, 0.03]	−0.00	[-0.02, 0.02]	−0.03	[-0.07, −0.00]	−0.01	[-0.03, 0.01]	**−0.02**	**[-0.04, −0.01]**
	$Education_{level2}$	−0.02	[-0.05, 0.02]	−0.01	[-0.02, 0.01]	0.02	[-0.01, 0.04]	0.01	[-0.01, 0.02]	**0.01**	**[-0.00, 0.01]**
	$Income_{level1}$	−0.00	[-0.05, 0.04]	0.01	[-0.01, 0.03]	−0.00	[-0.03, 0.02]	−0.00	[-0.02, 0.02]	−0.00	[-0.01, 0.01]
	$Income_{level2}$	0.03	[-0.01, 0.07]	−0.01	[-0.03, 0.01]	−0.02	[-0.05, 0.00]	−0.01	[-0.03, 0.00]	−0.01	[-0.02, 0.00]
	$Income_{level3}$	0.01	[-0.04, 0.05]	−0.00	[-0.02, 0.02]	0.02	[-0.01, 0.04]	0.01	[-0.01, 0.02]	−0.00	[-0.01, 0.01]
marg. R^2		.22		.29		.36		.41		.19	
ICC		.59		.55		.34		.60		.65	

Note. Continuous predictor variables are mean-centered and categorical predictors are effect coded; the dependent variables are on a scale from 0 to 1; fixed effects are reported as unstandardized regression coefficients (their 95 % CIs in brackets). Effects in bold are significant (i.e., 95 % CIs do not include 0); random effects are reported as standard deviations (*SD*s). Marginal R^2 quantifies the proportion of variance in a dependent variable explained by the fixed effects; T_1 = performance at first measurement occasion; ICC = intraclass correlation coefficient (based on a model with random intercepts only).

then conducted a model comparison between Models 2 and 3 (based on selection criterion LOOIC; smaller values are better; see Bürkner, 2017; McElreath, 2018). Comparisons and selection criteria of the models are displayed in Supplementary Material S2; the model equations are in Supplementary Material S3. In order to statistically account for initial individual differences in key sociodemographic variables that have been associated with individual differences in cognitive aging and to test if age-related longitudinal change can be observed over and above the initial differences in these variables, we also included sociodemographic variables (sex, income, education, initial health) and cognitive variables (at the first test occasion) in Models 2 and 3. For all analyses, categorical predictors were effect-coded and continuous predictors were mean-centered. Estimation of the model parameters relied on a Bayesian approach, using the package brms (Bürkner, 2017) in *R*. Convergence was satisfactory and the models provided a good fit to the data, as shown by the plots of the posterior predictive checks juxtaposed on the raw data (see Fig. S1 in Supplement S4; further details about model fit and convergence can also be found there). Overall, the Bayesian estimation procedure worked well and we can thus interpret the solutions from the Bayesian LMMs.

The estimates of fixed effects and random effects of the best fitting model for all cognitive variables are in Table 2. We report posterior means and 95 % Bayesian credibility intervals (which include a given model parameter with a probability of.95). As shown in Table 2, between-person variability was substantial for all cognitive variables and particularly large for PM (the random intercept *SD*s were about two times larger for PM than for episodic memory, working memory, or speed). Moreover, we found negative longitudinal age-effects on all cognitive variables, except for vocabulary. Age-related decline was most pronounced in working memory and speed, and least pronounced in verbal knowledge and PM (see also Fig. 1). Notably, individual differences in age-related decline (random slopes for the age-effects) only emerged for cognitive speed and vocabulary; these differences in intraindividual change were much smaller than the large variability in the intercepts.

Note that age-related decline was found after statistically accounting for demographic and other cognitive variables (at the first test occasion; see Table 2). As can be expected, performance on other cognitive variables at the first test occasion tended to be positively correlated with performance on any dependent variable. For instance, PM performance was generally higher for people with higher initial performance in tasks of episodic memory, of working memory, and of cognitive processing speed. By contrast, only few significant relations emerged between demographic/socioeconomic variables and cognitive performance: for vocabulary, we found that education level was somewhat relevant (lower performance with lower education levels). Moreover, there were unexpected sex differences in PM and episodic memory performance, which we briefly discuss later.

Discussion

Although studying cognitive aging has been of central interest for PM research since its early days (e.g., Einstein et al., 1996), there has only been a limited understanding of individual differences in PM development in older adulthood. In the current study we present a first in-depth examination of level of and change in older adults' PM performance and compare inter- and intraindividual differences to other central cognitive abilities—namely, episodic memory, working memory, processing speed, and verbal knowledge. We used linear mixed modeling with Bayesian parameter estimation on longitudinal data from 364 older adults assessed up to four times over up to more than 10 years to examine the following research questions.

How large are individual differences in older adults' PM?

We observed substantial variability between participants in the level of PM performance in older adulthood (Fig. 1 and Table 2). Despite advanced chronological age, certain old-old adults exhibited near-optimal PM performance across all PM tasks while other younger-old participants struggled to remember any of the prospective tasks. Notably, variability in level of PM performance was from nearly two to three times greater than of the other cognitive abilities. These findings underscore the capability of certain individuals – even among the oldest age groups – to excel in complex cognitive tasks such as PM tasks (see also Zuber et al., 2019a). They also highlight the necessity of further investigating cognitive and noncognitive variables (e.g., the role of motivation and incentives; see Horn, 2023; Horn, Schaltegger, Best, & Freund, 2023; Menéndez-Granda et al., 2023) and of the environment that contribute to successful PM performance.

Does PM decline within older age?

Extending previous longitudinal findings from Kamberis et al. (2021) and Sullivan et al. (2022) we found small but significant declines in PM performance in older adulthood across up to eleven years (see Table 1). This aligns with the broader cross-sectional PM literature reporting a (typically much larger) negative relationship between age and PM performance, particularly when PM is assessed in complex laboratory settings (for *meta*-analyses and overviews, see Henry et al., 2004; Horn & Freund, 2021; Ihle et al., 2013; Kliegel et al., 2008; Kliegel et al., 2016; Laera et al., 2023b; Zuber & Kliegel, 2020). However, all three longitudinal studies reported relatively small age-effects on event-based PM, corroborating the notion that age-effects may often be overestimated in cross-sectional studies (e.g., Schaie, 1994; also see subsequent sections). Kamberis et al. and Sullivan et al. even reported no longitudinal age-effects on other PM tasks (a naturalistic and a time-based PM task, respectively).

In this regard, one limitation of the present study is that it included only event-based but not time-based PM tasks. Although time-based PM may be particularly interesting to study in the context of aging because of its higher demand of self-initiated top-down control, so far, age-effects have been much more frequently investigated in event-based PM. Consequently, recent studies have underlined the need for more research on time-based PM (Joly-Burra et al., 2024; Laera, Brummer, Hering, Kliegel, & Horn, 2024; Rummel & Kvavilashvili, 2023; Zuber et al., 2024).

Are there individual differences in PM trajectories?

Our study did not uncover significant differences in participants' change of PM over time. Specifically, the inclusion of random slopes in the model for PM (alongside fixed effects for predictors and random intercepts) did not yield any notable enhancement in model fit or variance explained (see Supplement S2). While Kamberis et al. (2021) did not explore inter-individual variability in PM slopes, our findings diverge from those by Sullivan et al. (2022), who reported significant variability in event-based PM slopes. This discrepancy may stem from differences in study design and number of years that were covered. Our study encompassed a larger sample size (particularly at the later measurement occasions), more extensive time span, and broader age-range. Interestingly, additional age-stratified analyses conducted by Sullivan et al. also revealed a lack of significant variability in event-based PM slopes among old-old individuals. Together, these findings suggest that – although some variability in change may occur in young-old adults – *inter*individual differences in PM trajectories across the full span of older adulthood appear to be limited. That does not imply, however, that *intra*individual variability in PM performance is negligible. On the contrary, our additional analyses revealed that intraindividual variability across measurement occasions was greatest for PM (followed by working memory and then the other cognitive abilities; see Supplement S5). For example, intraindividual standard deviations of performance were nearly three times larger for PM than for processing speed. Given

that the reliability of the employed measures was largely acceptable and did not differ systematically across domains, these results indicate that both interindividual and intraindividual variability are particularly pronounced in PM.

Overall, the currently available longitudinal evidence suggests that while PM abilities generally follow a gradual, shallow decline in older adulthood (with relatively limited differences in this trajectory between individuals), there is considerable variability in PM performance – both between individuals (e.g., high versus low PM performances at any age) and within individuals (e.g., fluctuations in PM performance for a given individual across measurement occasions).

Individual differences and decline in episodic memory, working memory, processing speed, and verbal knowledge

As previous research often focused on examining longitudinal trajectories in one or few cognitive domains per study, one significant strength of the Zurich Longitudinal Study on Cognitive Aging is that its assessment includes five domains that are central to cognitive functioning and aging, allowing for more direct between-domain comparisons. Regarding *level of performance*, examining individual differences in episodic memory, working memory, processing speed, and verbal knowledge in this sample showed that there was substantial variability in level of performance between individuals across all cognitive variables (see Table 2 and Fig. 1). Aside from PM (see next section), variability was largest in working memory, for which the random effect was almost twice as large compared to verbal knowledge and 30 % larger than in episodic memory and processing speed. Overall, these results are in line with previous research showing large variability of cognitive performance in old age (e.g., Ghisletta et al., 2006; Hertzog, 2017; Tucker-Drob & Salthouse, 2011; Tucker-Drob et al., 2019), and suggesting that variability may be particularly large for tasks requiring higher-order cognitive control, including working memory or fluid intelligence (e.g., Hultsch et al., 2002; Joly-Burra et al., 2024; Tucker-Drob & Salthouse, 2011).

Regarding *age-related cognitive decline*, we found negative longitudinal age-effects on all cognitive variables – except for verbal knowledge, which remained relatively stable across older adulthood (see Table 2). Importantly, the current findings are among the first to systematically compare longitudinal trajectories across five core domains of cognitive functioning and show more pronounced decline in working memory and processing speed compared to episodic and prospective memory. This corroborates findings of previous research, also showing that age-effects are largest in working memory and processing speed, which may contribute to changes in other cognitive abilities (2005; Ghisletta & Lindenberger, 2003; Hertzog, Dixon, Hultsch, & MacDonald, 2003; Tucker-Drob et al., 2019). The finding of no age-related decline in verbal knowledge (as an indicator of crystallized intelligence) is consistent with previous studies and aligns with lifespan theories of intellectual functioning, suggesting substantially stronger age-related decline for fluid than crystallized cognitive abilities (e.g., Ghisletta et al., 2006; Horn & Cattell, 1967; Li et al., 2004; Park et al., 2002; Tucker-Drob et al., 2022).

Regarding *variability in change*, we found individual differences in age-related decline (i.e., random slopes for the age-effects) only for processing speed and verbal knowledge. Although this pattern partially aligns with the previous literature (e.g., Wilson et al., 2002), it stands in contrast to studies reporting less variability in verbal knowledge (e.g., Ghisletta et al., 2012). Possible reasons could involve statistical power (the present sample size was smaller, $N = 364$, than in Ghisletta et al., 2012, $N > 6000$) or the longitudinal study window (~10 years in the present study vs. ~ 20 years in Ghisletta et al., 2012). Importantly, differences in intraindividual change were much smaller than the large variability between persons, consistent with previous research reporting larger variability in intercepts than in slopes (e.g., Ghisletta et al., 2006; Lövdén et al., 2004).

Overall, analyses of both level and change in performance on episodic memory, working memory, processing speed, and verbal knowledge, show that when older adults are assessed in multiple waves across more than ten years, there is much larger variability between older adults in the level of cognitive performance in most domains than there is variability in change. Thus, age differences – although simpler to assess from a methodological perspective and easier to detect from a statistical perspective– do not necessarily coincide with within-person age-effects (i.e., age-related changes), and cannot be used as surrogates of change (also see Drewelies et al., 2022; Goh, An, & Resnick, 2012; Lindenberger, von Oertzen, Ghisletta, & Hertzog, 2011; Raz & Lindenberger, 2011; Thorvaldsson, Skoog, & Johansson, 2020). The overall pattern also highlights that the intricate relations between cognitive abilities, their trajectories, and other outcomes of interest can only be investigated through closely knit longitudinal studies in which the relationships of various cognitive abilities over time are examined jointly (see also Zuber et al., 2023b; for more details and additional literature on individual differences in cognitive domains other than PM, we also refer to the other contributions in this special issue).

How do individual differences in PM compare to the other cognitive abilities?

Two additional goals of the present study were to compare *levels* and *changes* in PM performance to the other cognitive abilities. First, analyses of the *levels* of performance showed that between-person variability was particularly large for PM compared to the other cognitive abilities (see Fig. 1 and Table 1). There are several reasons why PM may exhibit greater variability compared to other cognitive abilities. On the one hand, the methodological approach to assessing PM might contribute to this variability. PM tasks typically involve a limited number of potential responses per task, often with binary response options (i.e., 0 or 1 performance). This contrasts with other cognitive tasks that usually involve more responses and a broader range of response options.

From a conceptual perspective on the other hand, variability in PM performance may arise because PM is a complex cognitive construct that depends on the successful interaction of various cognitive processes, such as encoding, planning, attention, working memory, and episodic memory (see Ball et al., 2018, 2019; Brewer, Knight, Marsh, & Unsworth, 2010). Some individuals may exhibit intact mnemonic and attentional resources when these are assessed independently. However, when these resources must be employed simultaneously and sequentially – for instance, to detect a PM target, interrupt an ongoing activity, initiate PM task execution, and retrieve the correct PM intention – the cognitive load may overwhelm the system, leading to PM failures. Our analyses support this conjecture, showing that age-related effects on PM persisted even after accounting for individual differences in working memory and episodic memory. Therefore, to gain a better understanding of how and why PM changes in old age, future research should not only examine individual differences in cognitive abilities, but also investigate how effectively participants can integrate these abilities at the appropriate moments to achieve planned goals. This view also aligns with the Integrative Framework of PM, which highlights that beyond examining each contributing factor separately, it is essential to apply a more integrative perspective in order to disentangle what contributes to successfully forming, retaining, initiating and executing a prospective intention (Zuber & Kliegel, 2020; Zuber et al., 2024).

Second, analyses of the *changes* in performance, showed that age-related decline was least pronounced in PM compared to the other cognitive abilities (and was absent in verbal knowledge; see also Fig. 1). Although PM performance declined with age in the present study, it is important to reiterate that these declines were small and that intraindividual changes in PM were much smaller than the large variability between participants' levels of performance. Overall, our findings thereby support some conclusions from past cross-sectional research suggesting that age-effects in event-based PM may be smaller – at least

for certain event-based tasks – to other central cognitive abilities, such as working memory or processing speed (e.g., Einstein et al., 1996; Kvavilashvili, Kornbrot, Mash, Cockburn, & Milne, 2009, provide further discussion). Further, the present study represents the first systematic comparison of PM trajectories with individual differences in other central cognitive abilities. Yet, the magnitude of age-effects may strongly depend on characteristics and cognitive demands of the PM tasks (e.g., Uttl, 2008, for an overview), again highlighting the need for more longitudinal studies that include different types of PM tasks.

Conceptually, the smaller age-effects in PM than other cognitive tasks in the present study may appear somewhat surprising, as PM tasks are typically considered to rely strongly on multiple of these cognitive abilities, not only in order to remember the intention, but also to master ongoing-task demands in parallel to monitoring for and detecting the appropriate moment to perform the prospective task (e.g., Burgess & Shallice, 1997; Gonneaud et al., 2011; Laera et al., 2023a; Mahy, Moses, & Kliegel, 2014; Salthouse et al., 2004; Zuber et al., 2016; Zuber et al., 2019b). In view of the complex interaction of multiple cognitive processes that contribute to PM, from a theoretical perspective, age-effects could be expected to be even larger than in other cognitive abilities separately. Yet, here we found behavioral evidence on longitudinal trajectories across up to more than a decade, corroborating that negative age-effects may actually be smaller in PM than in each of the contributing cognitive abilities. Age-effects in PM that were smaller than those in other cognitive abilities may partially be explained by the fact that the event-based PM tasks used in the current study could more strongly rely on spontaneous cue detection (e.g., remembering to repeat "red pencil" when the experimenter said "red pencil"; detecting the background color of the computer screen changing to yellow). This notion is consistent with findings from some cross-sectional laboratory studies that also reported small or even no age-effects in similar event-based tasks (e.g., focal event-based tasks in Einstein et al., 1996; Zuber et al., 2019a). Similarly, although each of our PM tasks comprised three PM trials, conceptually, the Red Pencil and the Token task still closely resemble the one-off type of tasks that have been more often used to assess PM in naturalistic contexts (e.g., Kvavilasvhili et al., 2013). Although this may have the benefit of increasing the external validity of these measures, the previous literature indicates that these types of tasks could be less sensitive to detect age-effects (see the literature on the "Age-PM Paradox"; e.g., Haas et al., 2022; Haines et al., 2020; Rendell & Craik, 2000; Schnitzspahn, Kvavilashvili, & Altgassen, 2020). This issue poses an additional challenge for evaluating PM in extensive longitudinal studies, where numerous cognitive tests have to be administered within realistic time limits. Consequently, conducting a sequence of traditional PM tasks that comprise more PM trials and cognitively demanding ongoing tasks might prove difficult. Yet, future research will need to delve deeper into these inquiries by examining whether longitudinal age-effects in PM are more pronounced and overlap more closely with the trajectories of other cognitive abilities if the tasks comprise more PM trials and impose higher cognitive demands for the PM and ongoing tasks.

Can other cognitive and sociodemographic variables account for individual differences in PM?

We found that older adults' baselines abilities in episodic memory, working memory, processing speed, but not in verbal knowledge, predicted PM, with better baseline performance predicting better PM. This is in line with previous research that consistently associated PM performance with these underlying cognitive abilities in cross-sectional studies (for an overview, see Zuber & Kliegel, 2020). Yet, it is also important to note that (small) negative age-effects on PM persisted even when accounting for baseline cognitive abilities in episodic memory, working memory, processing speed, and verbal knowledge. Importantly, this suggests that the age-related declines in PM are not merely a function of decline in other cognitive abilities. Thus, regarding potential interventions to bolster PM or to promote the maintenance of PM in older adulthood, it may not be sufficient to target these abilities. Indeed, previous research shows that although cognitive abilities related to PM may be trainable as such, transfer to other non-trained abilities may be much more difficult (e.g., Diamond & Ling, 2016; Mewborn, Lindbergh, & Stephen Miller, 2017; Zuber et al., 2023a). Thus, it may be more promising to either directly target PM improvement, for example by teaching specific strategies or the efficient use of external memory aids (Hering, Rendell, Rose, Schnitzspahn, & Kliegel, 2014; Jones, Benge, & Scullin, 2021).

Considering sociodemographic variables that have been associated with other central cognitive abilities, we found that sex (but not education, income, or health) accounted for variability in older adults' PM. Unexpectedly, men showed slightly better PM performance than women, which aligns with Huppert et al. (2000), but stands in contrast to the more frequently observed absence of any sex-effects on PM (e.g., Au et al., 2018; Chan et al., 2010; Simard et al., 2019; Uttl et al., 2018). It currently remains unclear whether and why men (and older men in particular) would perform better in certain PM tasks. Although education did not have a direct effect on PM, men obtained more education than women in the cohorts we examined, and it is possible that men performed slightly better on the PM tasks partly due higher education and related sociocultural factors. However, we observed opposing sex differences in PM (i.e., advantage for men) compared to episodic memory (i.e., advantage for women), and these effects seem to be inconsistent and to vary across studies. It is therefore currently unclear whether and how sex might impact different aspects of performing cognitive tasks.

Similarly, although we did not find any of the other sociodemographic variables to relate to PM performance or trajectories in older age, there is currently not enough evidence to systematically conclude whether and through which mechanisms education, socioeconomic status, or health, contribute to PM across the lifespan. Although some of these variables may contribute to PM, there currently is no evidence that key sociodemographic variables can account for negative age-effects in PM; that is, age-effects persisted in our study after controlling for these variables.

Implications for measuring, scoring, and modeling PM

The present findings also indicate that PM performance not only shows much larger individual variability in old age compared to the other cognitive abilities, but that PM responses also follow a non-normal bimodal distribution. For example, Fig. S1 (in Supplement S4) illustrates that even when summed across all three PM tasks (i.e., when using an overall score based on nine separate PM trials in total), a considerable proportion of participants had a performance relatively close to zero (i.e., left peak of the solid dark line), indicating that these participants may have completely (or almost completely) forgotten any of the PM tasks; in contrast, other participants showed a performance close to 100 % accuracy, indicating that these participants responded accurately to most PM trials. Contrary to the requirements for linear models that assume normally distributed residuals, substantially fewer observations were located around the center of the observed PM distribution.

To account for this issue, we also modeled the PM data with an ordinal mixed model (which captured the observed PM distribution more accurately than the linear mixed model; as shown in the first panel of the bottom row of Fig. S2, actual observations did not match predicted models if modeled linearly, but almost perfectly overlapped with model predictions in the first panel of the top row, which was modeled assuming an ordinal PM variable). Because the conclusions regarding significant effects of predictors remained the same for the two model versions, we do not see a problem for interpretation in the present analyses. Nonetheless, it should be highlighted that (a) none of the other cognitive measures (e.g., episodic memory, processing speed) showed such strong violations of model assumptions and (b) it is not uncommon

that on the individual participant level, performance in PM tasks is often close to 0 or 1. Binary distributions of responses have been reported in prior studies (see e.g., Zuber et al., 2022, Fig. 3). This issue is important because the vast majority of PM studies have applied linear models (e.g., ANOVA or regression approaches) to examine PM performance and has treated PM as a continuous variable (but see Smith & Bayen, 2004). The present findings highlight that non-linear modeling techniques may be required to account for distributions of PM responses.

Another observation from the present study is that the correlations among the three PM tasks (at T1) were relatively low. As successfully performing a PM task requires the interplay of multiple cognitive processes, it might be that each of these three tasks deployed different cognitive processes to different degrees, thereby leading to additional variability and/or "noise" in PM performance (see also Ball, Vogel, & Brewer, 2019). Further, although reliability was acceptable for two of the PM tasks, it was.58 in the background change task, which might have additionally contributed to lower correlations. For future research, it would therefore be relevant to examine PM with tasks that all have high(er) reliability and to apply latent variable modelling in order to account for measurement error and task-specific variance.

Overall, the present findings underline that PM represents a complex cognitive construct that may be more difficult to capture compared to other cognitive abilities, both in terms of psychometric properties but also in terms of creating experimentally highly standardized and controlled tasks that simultaneously capture relevant daily behavior with high external validity. This highlights the need of developing more naturalistic yet experimentally controllable and psychometrically standardizable measures (for overviews of assessment tools for PM, see Blondelle, Hainselin, Gounden, & Quaglino, 2020, Blondelle, Sugden, & Hainselin, 2022). Recent studies using virtual reality technology present promising avenues for bridging laboratory and naturalistic measures of PM (Girardeau et al., 2023; Rose & Saito, 2024; Seesjärvi et al., 2022; 2023). In contrast to the commonly used computer tasks that comprise only a few PM trials or the more naturalistic one-off single-item PM tasks, virtual reality tools may help to design psychometrically more reliable measures while maintaining high external validity.

Concluding comments

Investigating individual differences in older adults' cognitive functioning with longitudinal studies is crucial because it allows examining potential differences in level and in change of performance and thus permits further exploring the mechanisms involved in aging and cognitive decline. Assessing cognitive abilities in older adults aged between 65 and 91 years, we found that variability in PM performance was substantially larger than in other abilities that are central to cognitive aging, namely episodic memory, working memory, processing speed, and verbal knowledge. Examining PM development in older adults for the first time across up to eleven years showed that age-related decline in PM is smaller than in other cognitive abilities and may actually be much smaller than suggested in previous cross-sectional studies.

Importantly, we found that significant interindividual variability and age-related decline in PM persisted, even after controlling for key cognitive correlates of PM as well as some of the main sociodemographic predictors of cognitive functioning in old age (i.e., education, socioeconomic status, sex, health). This highlights that although various variables contribute to successful PM in old age, more research is required to fully disentangle the underlying cognitive mechanisms of PM as well as their interaction with sociodemographic variables across the life course. Regarding further implications, it also implies that interventions specifically targeting successful prospective remembering may be more promising than bolstering these cognitive correlates that are typically postulated to underlie PM. This could, for example, be achieved through specific PM strategy training or learning how to use of mnemonic aids. Ultimately, in terms of successful aging, our in-depth examination of PM in comparison to other central cognitive abilities suggests that although many of the fluid cognitive abilities may generally decline as individuals grow older, even in complex and daily relevant cognitive tasks, such as PM, there is large variability in abilities in older adulthood. In many cases, longitudinal age-related decline in PM may be smaller than predicted by cross-sectional studies.

CRediT authorship contribution statement

Sascha Zuber: Writing – original draft, Formal analysis, Conceptualization. **Matthias Kliegel:** Writing – review & editing, Writing – original draft, Conceptualization. **Vera Schumacher:** Writing – review & editing, Investigation, Data curation. **Mike Martin:** Writing – review & editing, Conceptualization. **Paolo Ghisletta:** Writing – review & editing, Conceptualization. **Sebastian Horn:** Writing – original draft, Visualization, Formal analysis, Conceptualization.

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Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT (version 3.5) in order to draft, phrase, rephrase, and paraphrase parts of this manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication. Importantly, all theoretical, conceptual, and empirical contributions were made by the authors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jml.2024.104602.

Data availability

As it pertains to the broader Zurich Longitudinal Study on Cognitive Aging, non-aggregated data used for the present study cannot be stored on a public repository, but can be accessed through the corresponding author upon reasonable request.

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