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Who benefits most? Exploring age effects of episodic future thinking and enactment encoding on prospective memory from childhood to middle adulthood

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ABSTRACT
Failures to realise delayed intentions (prospective memory, PM) are common in everyday life, yet little is known about how PM performance can be improved. Deeper encoding during intention formation has been proposed to strengthen memory representations and facilitate later retrieval; however, no study has systematically compared different encoding strategies from childhood to middle adulthood. To address this gap, we examined the effects of two encoding strategies – episodic future thinking (EFT; mental practice) and enactment encoding (EE; physical practice) – on PM performance across four age groups. A total of 373 participants were tested, including children ($n = 90$), adolescents ($n = 96$), young adults ($n = 97$), and middle-aged adults ($n = 90$). Participants were randomly assigned to an EFT, EE, or standard encoding condition and completed a novel computerised PM task. A significant main effect of encoding condition emerged. Overall, participants in the EE condition outperformed those in both the EFT and standard encoding conditions, with no evidence that this benefit differed by age group. Contrary to expectations, EFT did not improve PM performance relative to standard encoding. This unexpected finding is discussed in terms of cue focality and high ongoing task demands.

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Independent actions and self-determination in everyday life are indispensable components of autonomous living. This also includes remembering to carry out intended actions at a later point in time, such as later the same day or week. These plans can be rather trivial, e.g., remembering to buy more washing powder after work. However, they can also be of high importance, such as remembering to pass on an important message or to switch off the iron before leaving home. The cognitive ability to successfully remember to carry out future intentions at the appropriate moment is known as prospective memory (PM; McDaniel & Einstein, 2000).

Conceptually, the process of prospective remembering can be divided into four distinct phases, each of which relies on different cognitive abilities (e.g., executive functions, episodic memory; Kliegel et al., 2002). First, the intention for a future action is formed, planned, and encoded (intention formation). Second, the intended action must be retained in episodic memory (intention retention) while other ongoing activities are being performed. The third (intention initiation) and fourth (intention execution) phases require the individual to monitor for the appropriate moment to initiate the intended action, inhibit performing the ongoing activity, and switch to executing the intended action (Kliegel et al., 2011). Based on the cue indicating the appropriate moment to initiate the intended action, research differentiates between event-based and time-based PM tasks (McDaniel & Einstein, 2000). For event-based PM tasks, the action should be performed after the presentation of a specific external cue (e.g., remembering to return money previously lent by a friend the next time I meet them), while for time-based PM tasks the action should be performed at a specific time point or after a predefined time period has elapsed (e.g., remembering to take the cake out of the oven after half an hour; Rummel & Kvavilashvili, 2023). Given that time-based PM tasks require self-initiated time monitoring and do not comprise external cues that may facilitate retrieval by supporting the intention to spontaneously "pop up" in one's mind due to the associative link between the external cue and the encoded intention (McDaniel et al., 2015), they are

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considered to be more challenging than event-based tasks. Importantly though, not all event-based tasks rely on spontaneous intention retrieval, but the extent to which they require strategic, executive control resources depends on task and individual characteristics (for details see the Multiprocess Framework, McDaniel & Einstein, 2000). For example, when PM cues are focal to the information processed as part of the ongoing task, spontaneous, relatively automatic bottom-up processes may trigger intention retrieval and place only minimal demands on cognitive resources (Kliegel et al., 2002). In contrast, non-focal PM cues that are not part of the information processed during the ongoing task may require effortful, strategic monitoring to be detected (McDaniel et al., 2015).

PM development follows an inverted U-shaped pattern across the lifespan, with performance increasing throughout childhood, peaking in adolescence or young adulthood, and decreasing again from middle adulthood onwards (e.g., Kliegel et al., 2008; Stelz & Altgassen, 2025; Zimmermann & Meier, 2006), mirroring the developmental pattern of executive functions (Best & Miller, 2010; Zelazo et al., 2004).

Successful PM performance in everyday life is crucial for developing and later maintaining an independent life, and PM failures can negatively affect individuals' school or work performance, social relationships, and health (Ellis & Freeman, 2008; Haas et al., 2020; Smith et al., 2000). An everyday example of PM failure in children and adolescents might be forgetting to put on a bicycle helmet on the way to school, which, in the event of an accident, may lead to serious physical consequences. In adulthood, an everyday example of PM failure might be forgetting to pay one's bills, which may result in additional costs. These examples and their unfavourable outcomes clearly demonstrate the critical importance of finding ways to enhance the execution of intended actions. According to the Multiprocess Framework (McDaniel & Einstein, 2000) efficient intention formation (e.g., by using a beneficial encoding strategy to enhance learning) during the intention formation phase may reduce the need for resourceful strategic monitoring, rather automatically prompt retrieval of the intended action and thus increase the likelihood for the successful execution of a delayed intention (Jones et al., 2021). To date, there has been a scarcity of research to examine the effects of applying encoding strategies in the intention formation phase on PM performance in both laboratory and everyday life. The few existing studies focused on individual age groups or narrow age bands (e.g., children, young vs old adults), neglecting certain age groups (e.g., adolescents, middle adulthood), and findings are inconsistent (Altgassen et al., 2017; Cottini et al., 2021; Faustmann & Altgassen, 2024). Systematic comparisons of encoding strategies across a broad developmental period from childhood to middle adulthood are lacking, and it remains unclear whether different age groups benefit more from a specific strategy than others. Therefore, this study set out to examine, for the first time, the effects of two encoding strategies on prospective remembering from childhood to middle adulthood, including underrepresented and/or unexamined age groups such as adolescents and middle-aged adults. Older adults were not included because pilot testing suggested that the game-based task was too fast and relatively unfamiliar for this age group, likely due in part to lower levels of computer-game experience. As a result, performance would have been difficult to interpret independently of task familiarity.

A strategy that has been shown to enhance PM performance across different developmental populations is episodic future thinking (EFT = mental practice). EFT refers to the cognitive ability to mentally project oneself into a possible future situation and to pre-experience it in advance (Schacter et al., 2008). EFT involves detaching oneself from the present and recombining different previously experienced elements stored in episodic memory (e.g., details about places, people, and objects) to flexibly generate new mental images (Buckner & Carroll, 2007; Schacter & Addis, 2007). EFT starts to develop around the ages of three or four years (Atance & Jackson, 2009) and continues to develop throughout middle childhood and adolescence (Addis et al., 2008; Ferretti et al., 2018). After a peak in young adulthood, EFT decreases again with age (Addis et al., 2010). It has been suggested that EFT may especially be involved in the intention formation phase of PM as people might visualise in detail when and how they will carry out their intention while forming it (Paraskevaides et al., 2010). The imagination of the visual-spatial context in which the delayed intention will later be executed may lead to deeper encoding (and therefore to stronger episodic memory traces) and may create strong associations of the intention and the future execution context, resulting in more automatic retrieval of the planned intention when the individual later encounters the imagined context, thereby reducing executive functioning demands (de Vito et al., 2012). Thus, engaging in EFT might reduce resource-demanding strategic processes during the delay period and facilitate retrieval. It has been suggested that EFT could have a stronger impact on event-based PM tasks due to their specific, external cues as compared to time-based PM tasks as it might be more difficult to visualise the passage of time or a specific time point than a specific external cue.

Consistently, several studies that instructed participants to imagine the later execution of an intended action in detail (EFT) while encoding the task reported increased PM performance (e.g., Altgassen et al., 2015, 2017; Kretschmer-Trendowicz et al., 2016; Nigro et al., 2014; Paraskevaides et al., 2010). For example, Kretschmer-Trendowicz et al. (2016) compared two groups of 5- to 7-year-old children (EFT condition vs. standard encoding) in a picture-naming task. Children in the EFT condition were told to mentally visualise task execution and showed superior PM performance compared to controls. Older children benefited more from EFT instructions than younger children, possibly due to the ongoing development of EFT throughout childhood which might not be sufficiently developed in children under the age of 7 to support PM performance (e.g., Nigro et al., 2014). In a later study, Kretschmer-Trendowicz et al. (2019) extended the findings of beneficial effects of EFT on PM in 10–12-year-old children using a more complex PM task with real life demands. Cottini et al. (2021) explored the effects of EFT, performance predictions (as a measure of metacognitive ability) and a combination of EFT and performance predictions on the execution of a one-back picture classification task in children aged 8–10 years. Interestingly, the authors only found enhanced PM performance in the combined condition (EFT + performance predictions) but no beneficial effects for the single encoding strategies. Altgassen et al. (2017) compared the effects of EFT in adolescents and young adults using a picture-based 2-back working memory task. Results revealed that only adolescents benefited from engaging in EFT during intention formation, while young adults' performance did not improve compared to standard encoding. Authors concluded that young adults' spontaneously applied strategies might have been disrupted by the request to use EFT which resulted in impaired PM performance. To investigate whether older adults would also benefit from engaging in EFT, Altgassen et al. (2015) compared younger and older adults' performance in the Dresden Breakfast task in two conditions (EFT at intention formation vs. a standard encoding control condition). Both younger and older adults showed enhanced PM performance in the EFT condition, but no differential age effects were observed. A further study by Ma and Zhang (2024) reported significant effects of a prolonged 5-minute EFT engagement during the encoding of PM tasks in both younger and older adults, although the effect in older adults was only marginally significant. The authors concluded that the beneficial effects of EFT might be more pronounced in younger adults than in older adults. In a second experiment, the same authors compared experimenter-guided vs. self-guided EFT in both groups. Results revealed that experimenter-guided EFT only led to better PM performance in older adults, while for younger adults effects did not differ between the two conditions. Empirical evidence suggests that beneficial effects of EFT on PM may also extend beyond the standard laboratory setting to real life (e.g., Neroni et al., 2014) and may also emerge in clinical populations (e.g., patients with Korsakoff syndrome; Lloyd et al., 2020; traumatic brain injuries; Mioni et al., 2017; but see Faustmann & Altgassen, 2024, for no beneficial effects in autism). Taken together, there is strong evidence for increased PM performance following EFT during intention formation across various age groups. To date, most studies examined the impact of EFT on event-based PM performance (Altgassen et al., 2015, 2017; Brewer & Marsh, 2010; Cheie et al., 2021; Cottini et al., 2021; Kretschmer-Trendowicz et al., 2016, 2019; Lloyd et al., 2020; Ma & Zhang, 2024; Mioni et al., 2017; Neroni et al., 2014; Nigro et al., 2014; Terrett et al., 2016, 2019), while only few studies explored its effects on time-based PM performance (Altgassen et al., 2015; Cheie et al., 2021; Faustmann & Altgassen, 2024; Mioni et al., 2017; Terrett et al., 2016, 2019). Therefore, the aim of the present study was to add further evidence to the impact of EFT on both event-based and time-based PM.

Another encoding strategy predominantly used in retrospective memory and not yet widely explored in PM research is enactment encoding (EE = physical practice). During EE, the individual performs a physical action associated with the to-be-remembered word/intention/phrase. The beneficial effect of enactment is thought to stem from additional brain activation during encoding (e.g., particularly in the supramarginal gyrus; Grèzes & Decety, 2001; Russ et al., 2003). In a traditional standard encoding PM condition, participants typically read instructions, see pictures, or receive verbal instructions, thus, they store verbal/semantic and imaginary information of the intended action in episodic memory. Enacting a related action linked to the delayed intention might result in a stronger focus on action-relevant information, promoting the integration of action and retrieval cue, leading to deeper encoding and stronger memory traces (Engelkamp, 1995; Kormi-Nouri, 1995). This additional motoric information may enhance both encoding and retrieval processes.

In line with these considerations, Pereira et al. (2012a) compared young and old adults who were either instructed to read aloud instructions at encoding or to physically simulate each task twice. Both age groups showed better PM performance when they were asked to physically simulate the intention instead of simply reading it aloud (for similar results see: Freeman & Ellis, 2003; Li et al., 2022; Pereira et al., 2012b). This enactment advantage was also found in clinical populations with impaired executive functions and/or episodic memory (e.g., mild cognitive impairment; Pereira et al., 2015; Pereira et al., 2018, or autism; Faustmann & Altgassen, 2024 – although only for time-based PM, not for event-based PM). Similarly to research on retrospective memory (Mecklenbräuker et al., 2011), there is some evidence that EE does not improve PM performance in children younger than 7 years (Li & Wang, 2015; Passolunghi et al., 1995). In contrast, 8–9-year-old children (Li & Wang, 2015) and 10–11-year-old children have been shown to benefit from EE when completing PM tasks (Passolunghi et al., 1995). No study to date has investigated the impact of EE on PM in adolescents. It was therefore the primary aim of the present study to examine the effects of two different encoding strategies, compared with a standard encoding condition, on PM performance across different age groups (children, adolescents, young adults, and middle-aged adults).

Following previous evidence indicating an inverted U-shaped developmental pattern of PM across the lifespan, we expected children to show the lowest PM performance, followed by adolescents, middle-aged adults and young adults (Kliegel et al., 2008; Kretschmer-Trendowicz et al., 2016; Mattli et al., 2014; Stelz & Altgassen, 2025; Zimmermann & Meier, 2006). We also expected to find the same developmental pattern in executive functions (Best & Miller, 2010; Zelazo et al., 2004). Moreover, given that time-based PM tasks require more effortful processing (e.g., executive function) due to the absence of external cues (Einstein et al., 1995; McDaniel & Einstein, 2007), we expected all age groups to show better event-based PM performance compared to time-based PM (Jäger & Kliegel, 2008; Stelz & Altgassen, 2025). Regarding the effects of the encoding strategies, we predicted that, compared to standard encoding, both EFT (= mental practice) and EE (= physical practice) would improve PM performance in all four age groups (e.g., Altgassen et al., 2015; Kretschmer-Trendowicz et al., 2016, 2019; Li & Wang, 2015; Passolunghi et al., 1995; Pereira et al., 2012a; Pereira et al., 2012b). We further expected children and young adults to benefit least from the use of both strategies – children because executive functions and episodic memory are still developing, and young adults because their performance is already relatively well established – followed by middle-aged adults and adolescents. Across all age groups, we expected larger benefits of the encoding strategies for the event-based than for time-based PM task.

Method

Participants

The required sample size was estimated a priori with a power analysis (Table 1) using the programme G*Power (version 3.1.9.7; Faul et al., 2007). Results revealed that a total sample size of $N = 360$ should be large enough to demonstrate a mean interaction effect $f = .25$ with an alpha level of .05 and a power of .80. In total, 90 children (7–10 years, $M = 8.57$, $SD = 1.05$), 96 adolescents (12–16 years, $M = 14.32$, $SD = 1.04$), 97 young adults (18–25 years, $M = 22.02$, $SD = 2.11$), and 90 middle-aged adults (30–55 years, $M = 42.79$, $SD = 7.2$), all of them indicating German as their first language, took part in the present study. Participants within their age group were randomly assigned to one of the three encoding conditions (i.e., standard encoding, EFT or EE) with approximately $n = 30$ in each condition (see Table 2 for details). Children and adolescents were recruited from local schools, while all young adults were psychology students at the local university. Middle-aged adults were recruited through the local community, and via advertisement at local universities, gym groups or online (e.g., neighbourhood apps, social media). As compensation for participating in the study, psychology students received course credit and all other participants 10 €. All participants were typically developed; exclusion criteria for participation in the study were self-reported history of psychiatric, developmental or neurological disorders. Participants' verbal abilities were assessed using the German version of the vocabulary subtest of the Wechsler Intelligence Scale for Children – Fifth Edition (WISC-V, Petermann, 2017), and the vocabulary subtest from the Wechsler Adult Intelligence Scale Fourth Edition (WAIS- IV; Petermann, 2012), respectively. All participants performed within the normal range. The study was conducted in accordance with the Declaration of Helsinki and was approved by the local ethics committee. All participants gave written informed consent prior to study participation. Only children and adolescents whose parents had also given written informed consent were allowed to participate.

Materials

PM task

To assess PM performance, across all age groups a novel task, the Mainz Garbage Truck, was used (see Figure 1 for an image of the User Interface). Similarly to the Cyber-Cruiser (Kerns, 2000) and Dresden Cruiser (Voigt et al., 2011), the task was designed as an engaging computer game asking participants to drive a garbage truck to collect garbage cans. The ongoing task consisted of navigating a garbage truck on a three-lane street using the left and right arrow keys to steer the truck on the horizontal axis (left-right) and to collect all blue garbage cans (correct garbage cans) while avoiding all black and green garbage cans (incorrect garbage cans) as well as avoiding bumping into construction sites. In total, the task included 615 ongoing task items (i.e., garbage cans), with blue, black, and green garbage cans being distributed approximately equally across the task. Ongoing task performance was operationalised as accuracy, calculated as the proportion of correctly collected garbage cans relative to the total number of collected garbage cans. Within the game, time- and event-based PM tasks were embedded. For the time-based PM task, participants were to

Table 1. Individual difference variables.

	Children $n = 90$ M (SD)	Adolescents $n = 96$ M (SD)	Young adults $n = 97$ M (SD)	Middle-aged adults $n = 90$ M (SD)	Statistics
Age (years)	8.8 (1.1)	14.3 (1.0)	22.0 (2.1)	42.8 (7.2)	F (3,369) = 1425.62, $p < .001$, $\eta_p^2 = .92$
Gender	57 F, 33 M	50 F, 46 M	65 F, 32 M	39 F, 51 M	χ^2 (3) = 13.18, $p = .004$
Verbal abilities	11.5 (3.2)	11.6 (2.4)	10.5 (1.6)	10.6 (1.7)	F (3,369) = 5.54, $p < .001$, $\eta_p^2 = .04$

Note: F: female; M: male; Verbal abilities are presented as age-scaled scores from the vocabulary test from WISC-V and WAIS-IV, resp.

Figure 1. Screenshot of the user interface of Mainz Garbage Truck.

remember to refill the fuel of the garbage truck on time. Participants were informed that the fuel level would decrease steadily from 100% to 0% every 45 s. Participants were able to check the fuel level by pressing the space button (task monitoring). As a result, the fuel level was displayed in the upper centre of the screen for 3 s. Absolute task monitoring was defined as the total number of fuel checks across the task. Strategic time monitoring was operationalised as an increase in fuel checks toward the final interval of each 45-s cycle and was analysed as the distribution of fuel checks across three successive intervals (1–15 s, 16–30 s, 31–45 s), aggregated across the five time-based PM trials (Joly-Burra et al., 2022). More strategic monitoring was reflected in a higher number of checks in the final interval. If the fuel level dropped below 10%, a refill was possible by pressing the "M" key on the keyboard. If the level was above 10% during the check, a refill was impossible. If the time window (below 10% to 0% – a total time of 4.5 s) for the refill was missed, the fuel tank automatically refilled itself. The time window for completing the time-based PM task was defined analogously to that used in the other time-based tasks (e.g., 2-back task; Altgassen et al., 2019). The event-based PM task consisted of remembering to collect bigger white garbage cans that stood in front of houses with blue roofs on the sides of the road. Usually, all roofs of the houses presented on the roadside were red. Participants were instructed that when they would see a large white garbage can in front of a house with a blue roof, they had to navigate the truck to the side of the road where the large white garbage can was standing and had to press the "B" button while passing the garbage can. In total, there were five time-based and five event-based PM tasks. The five event-based PM targets appeared at 17.05 s (left side), 61.28 s (left side), 80.05 s (right side), 139.58 s (left side), and 221.45 s (right side). Target positions were fixed across participants and were not additionally counterbalanced beyond their distribution across the left and right sides of the road. Ongoing task load was present at all event-based PM target moments, as garbage cans continued to appear throughout the task and participants therefore had to decide whether to prioritise the ongoing task or the event-based PM response. This basic competition between ongoing task and PM demands was thus comparable across all five event-based PM targets. The dependent variable was the number of correctly executed PM tasks for each PM cue type. To ensure all participants were able to perform the tasks and to familiarise them with the correct button-use, participants completed a practice run (123 s) including both time- and event-based tasks. After a filled delay of ten minutes, the main task was performed. The main task lasted 263 s.

Individual differences

Colour Stroop. The Stroop Test (Stroop, 1935) was used to measure inhibition. Participants were shown three different lists of words or colours in succession. The first list contained 32 colour words written in black, which individuals had to read out as quickly as possible. Thereafter, participants were presented with a list consisting of 32 coloured strokes and were asked to name the colours in the order presented as quickly as possible (congruent stimuli). At last, a third list was shown with coloured printed colour names, but the printed colour and the printed word did not correspond (e.g., the word "red" was written in green; incongruent stimuli). Participants were asked to name the printed colour as quickly as possible (while inhibiting reading out the word). The dependent variable was obtained by subtracting the time taken in naming congruent from incongruent lists. Thus, lower reaction times indicate better inhibitory control.

Trail making test. The Trail Making Test (TMT; Reitan, 1992) is a widely used neuropsychological assessment tool to measure cognitive flexibility (switching). It comprises two subtests, Parts A and B, which feature an exercise example and 25 circles that must be connected. For Part A, the objective was to connect the numbers in ascending order from 1 to 25, while for Part B, the goal was to alternate between numbers (1–13) and letters in alphabetical order from A to L (hence, 1-A-2-B etc.), as quickly as possible. The TMT score (dependent variable) for each participant was determined by subtracting the time taken to finish Part A from the time taken to finish Part B. Lower scores indicate better switching abilities.

Backward digit span. Working memory performance was assessed with the backward digit span test from the Wechsler Intelligence Scale for Children – Fifth Edition (WISC-V, Petermann, 2017), or the from the Wechsler Adult Intelligence Scale Fourth Edition (WAIS- IV; Petermann, 2012), by reading out series of digits at the rate of one item per second. Participants were instructed to recall the named numbers from back to front. The score can range from 0 to 16 points with higher scores indicating better working memory performance.

Tower of Hanoi. The Tower of Hanoi (ToH) was used to measure planning ability. In the present digital version, the ToH required the movement of disks of different sizes across three pegs from an initial state (all disks arranged on the left side as a pyramid) to a target state (all disks arranged on the right side as a pyramid) in as few moves and as quickly as possible. After a practice trial with two-disks to familiarise participants, they completed a three-disk and four-disk version. The dependent variable was the number of moves in the three- and four-disk versions.

Episodic memory. The German version of the Rey Auditory Verbal Learning Test (RAVLT; Rey, 1964) was used to measure episodic memory across all age groups. Individuals were verbally presented five times with the same 15-word list (List A), and each presentation was followed by a free recall trial. Participants could recall the words in any order. Words were presented at 1-s intervals; no feedback was given about the number of correct responses, repetitions, or errors. This was followed by the one-time presentation of another 15-word list (List B). Immediately following the presentation of List B, and without any additional presentation, participants were asked to recall the words from the original list (List A). After a 20-minute delay, participants were again required to recall the words from List A. The dependent variable was the number of correctly recalled words after the delay.

Gaming experience. Gaming experience was assessed using a brief self-developed questionnaire. Participants were asked on how many days they had played games during the past two weeks (*not at all, 1–2 days, 3–7 days, more than 7 days*). They also indicated the device they primarily used for gaming (*mobile phone, computer/laptop, console, console via television, other, I do not play*) and the type of games they predominantly played (*jump-and-run, shooter, sports games, strategy/simulation, action and adventure, puzzle games, I do not play*). In addition, participants reported their overall years of gaming experience as well as their years of experience with jump-and-run games, the latter being assessed separately because this genre was considered most similar to the paradigm used. Response options for both items were *less than 1 year, 1–2 years, 2–4 years, more than 4 years*, and *I have never played*.

Procedure

Each participant was tested individually in a session that lasted approximately 45 min. At first, all participants completed the first six trials of the RAVLT, followed by questionnaires assessing demographic variables and gaming experience, which were administered via the online platform SoSci Survey (Leiner, 2019). Thereafter, participants worked on the vocabulary subtest of the WISC-V or WAIS-IV and were then introduced to the Mainz Garbage Truck task and completed the one-minute practice trial. All participants were randomly assigned to one of the three encoding conditions (EFT, EE, control condition). In the standard encoding condition, after having been introduced to the Mainz Garbage Truck task and completing the practice run, participants immediately worked on two executive function tasks (Colour-Stroop, Trail-Making-Task) as a filled delay before performing the actual testing block of the Mainz Garbage Truck task.

In the EFT condition (Faustmann & Altgassen, 2024), after having been introduced to the Mainz Garbage Truck task and completing the practice run, participants were instructed to practice future thinking using an unrelated everyday example (e.g., imagine brushing their teeth at night before going to bed). Participants were first asked to imagine the specific situation for 20 s with their eyes closed in as much detail as possible. They were then asked to report aloud for 20 s what they had visualised. Thereafter, participants were asked to indicate the vividness of the imagery and the degree of pre-experiencing this event on a 5-point Likert scale. The practice phase took about 3 min. Participants were then asked to apply future thinking to all three core gaming components of the Mainz Garbage Truck: (1) imagine navigating the garbage truck by using the right and left arrow key (ongoing task), (2) imagine collecting the large white garbage cans at the roadside by pressing the "B" button while passing the house (event-based PM task) and (3) imagine refuelling the garbage truck by pressing the "M" key on the keyboard (time-based PM task). Finally, participants rated again the vividness of their imagery and the degree of pre-experience on a 5-point Likert scale.

In the EE condition, after having been introduced to the Mainz Garbage Truck task and completing the practice run, participants were demonstrated three real life practical exercises one at a time by the experimenter, each of them corresponding to one of the three core components of the PM task (e.g., Pereira et al., 2012a). The corresponding movement for the ongoing task of driving the Garbage Truck consisted in moving an imaginary steering wheel from left to right. The participants symbolically placed their hands on an imaginary steering wheel in the air in front of them and turned their arms once to the left and once to the right. The movement for the event-based task consisted of dragging an imaginary garbage can behind them while walking three steps. The movement for the time-based task consisted of a refuelling movement in which three fingers were formed into a fuel nozzle and one pretended to insert the gun into the fuel filler. Participants were asked to repeat each movement three times. Introductions to both experimental conditions took about 5–7 min. Last, all participants performed the backward digit span and the Tower of Hanoi.

The study was preregistered on the Open Science Framework (OSF), where the preregistration and data are publicly available at https://osf.io/p23cu. Some deviations from the preregistration should be noted. First, the final age ranges differed slightly from those originally preregistered, particularly for the child, adolescent, and middle-aged groups due to recruitment constraints. Second, PM performance was analysed using raw indices rather than the preregistered proportional scores because, given the small number of possible PM responses per cue type (five), raw scores appeared more directly interpretable and less artificial than percentage-based scores. Finally, we excluded the VVIQ (Vividness of Visual Imagery Questionnaire; Marks, 1973) because during data collection we observed that especially children had difficulty understanding the questionnaire, raising concerns about the validity of the measure in this sample. In addition, task monitoring was analysed as a standard task-related measure, although it had not been explicitly specified in the preregistered analysis plan. We also added a gaming-experience measure shortly before the start of the study, following pilot testing, because it appeared to be a potentially confounding variable; however, by that point the preregistration had already been completed.

Results

Individual differences

One-way analyses of variance (ANOVA) with age group (children, adolescents, young adults, middle-aged adults) and encoding condition (EFT, EE, control condition) as between-subject variables were conducted to explore possible group differences in executive functioning and episodic memory. For more detailed information see Table 2.

Regarding inhibition, a significant age group effect was observed, F (3, 361) = 50.12, $p < .001$, $\eta_p^2 = .29$, but no effect of encoding condition, F (2, 361) = .52, $p = .60$, $\eta_p^2 = .003$. Children showed the lowest inhibitory control compared to all other age groups (all $ps < .001$). Adolescents and young adults ($p = .17$) as well as adolescents and middle-aged adults ($p = .94$) did not differ in their inhibitory ability, but there was a significant decline in inhibition from young to middle-aged adults ($p = .04$). The interaction between age group and encoding condition was not significant, F (6, 361) = 1.12, $p = .35$, $\eta_p^2 = .02$, indicating no differential age effects across encoding conditions (EFT, EE, standard encoding).

There was also a significant effect of age group regarding switching abilities, F (3, 361) = 52.62, $p < .001$, $\eta_p^2 = .30$, but no effect of encoding condition, F (2, 361) = .43, $p = .43$, $\eta_p^2 = .002$ and no interaction, F (6, 361) = 1.55, $p = .16$, $\eta_p^2 = .03$. Again, children showed the lowest abilities compared to the other groups (all $ps < .001$). Switching abilities increased significantly from adolescents to young adults ($p = .02$). There was no difference between adolescents and middle-aged adults ($p = .81$) and between young adults and middle-aged adults ($p = .22$).

Table 2. Mean and standard deviations of executive function and episodic memory across age groups and conditions.

	N	Inhibition *M* (*SD*)	Switching *M* (*SD*)	Working memory *M* (*SD*)	Planning (3-disk) *M* (*SD*)	Planning (4-disk) *M* (*SD*)	Episodic memory *M* (*SD*)
Children							
EFT condition	30	21.0 (13.6)	75.0 (32.3)	8.0 (2.3)	9.9 (3.1)	24.9 (8.0)	9.8 (2.5)
EE	29	20.8 (9.5)	69.8 (53.8)	8.3 (1.8)	9.8 (2.7)	25.7 (8.2)	8.6 (2.1)
Control condition	31	25.1 (16.1)	57.5 (27.3)	9.0 (1.7)	9.7 (2.4)	25.8 (9.3)	10.0 (2.6)
Adolescents							
EFT condition	32	12.1 (5.1)	34.8 (14.0)	10.9 (2.0)	9.2 (2.8)	23.3 (5.9)	10.9 (2.5)
EE	32	11.4 (8.0)	35.2 (14.0)	10.8 (2.2)	9.1 (2.7)	23.6 (7.7)	11.5 (2.3)
Control condition	32	9.7 (6.8)	37.6 (16.4)	10.3 (2.4)	9.3 (2.8)	24.3 (9.7)	11.3 (1.8)
Young adults							
EFT condition	33	8.3 (4.9)	22.7 (9.1)	10.8 (2.2)	8.2 (1.9)	22.2 (5.6)	13.6 (1.5)
EE	32	9.0 (4.2)	25.9 (14.3)	10.3 (2.3)	8.0 (1.6)	21.9 (5.5)	12.7 (2.3)
control condition	32	8.7 (5.1)	29.2 (15.2)	10.6 (2.0)	8.3 (2.1)	22.1 (6.5)	13.7 (1.4)
Middle-aged adults							
EFT condition	30	12.2 (5.5)	34.6 (31.6)	9.5 (2.5)	8.3 (2.3)	22.0 (9.5)	12.6 (2.2)
EE	30	10.6 (4.3)	31.8 (15.5)	9.5 (2.1)	8.5 (2.6)	22.2 (7.1)	12.8 (2.0)
Control condition	30	12.5 (5.3)	31.6 (16.0)	9.5 (2.8)	8.6 (2.6)	21.6 (7.9)	12.4 (2.6)

Note: EFT: episodic future thinking; EE: enactment encoding.

Regarding working memory, again a significant age group effect was found, F (3, 361) = 21.50 $p < .001$, $\eta_p^2 = .15$, but no effect for encoding condition, F (2, 361) = .13, $p = .88$, $\eta_p^2 = .001$ and no interaction, F (6, 361) = .86, $p = .52$, $\eta_p^2 = .01$. While children showed the lowest working memory abilities compared to all other age groups (all ps < .009), adolescents outperformed middle-aged adults ($p = .001$) but not young adults ($p = .99$). Young adults showed better working memory performance compared to middle-aged adults ($p = .003$).

The results regarding planning abilities in the 3-disc version of the Tower of Hanoi task showed a significant main effect for age group, F (3, 361) = 7.63 $p < .001$, $\eta_p^2 = .06$, but no effect for encoding condition, F (2, 361) = .08, $p = .93$, $\eta_p^2 = .000$ and no interaction effect, F (6, 361) = .08, $p = .99$, $\eta_p^2 = .001$. Young adults outperformed children and adolescents (ps < .003) but showed comparable abilities to middle-aged adults ($p = .84$). Children and adolescents did not differ in their planning abilities ($p = .33$). Results from the 4-disc version also revealed a significant age group effect, F (3, 356) = 4.11 $p = .007$, $\eta_p^2 = .03$, but no effect for encoding condition, F (2, 356) = .06, $p = .94$, $\eta_p^2 = .000$ and no interaction effect, F (6, 356) = .09, $p = .99$, $\eta_p^2 = .001$. Children were outperformed by young ($p = .02$) and middle-aged adults ($p = .01$). All other groups did not differ in their performance (all p's > .38).

In terms of individual differences in episodic memory, a significant main effect of age group was found, F (3, 361) = 57.52 $p < .001$, $\eta_p^2 = .32$, but no effect for encoding condition, F (2, 361) = 1.34, $p = .26$, $\eta_p^2 = .007$ and no interaction, F (6, 361) = 1.64, $p = .13$, $\eta_p^2 = .03$. Between children and adolescents and again between adolescents and young adults there were significant differences in episodic memory, showing an increase in performance from childhood to young adulthood (all ps < .001). There was no difference between young and middle-aged adults.

PM performance

A 4 × 3 × 2 mixed analysis of variance (ANOVA) was carried out to investigate the effects of age group (children, adolescents, young adults, middle-aged adults), encoding condition (EFT, EE, control condition), and PM cue (event-based, time-based) on PM performance (see Table 3). Age group and encoding condition were between-subjects variables, and PM cue was a within-subject variable. The analysis revealed a significant main effect of PM cue, F (1, 361) = 39.63, $p < .001$, $\eta_p^2 = .10$, indicating that overall, participants completed more event-based than time-based PM tasks. There was also a significant main effect of age group, F (3, 361) = 59.21, $p < .001$, $\eta_p^2 = .33$. Post hoc Tukey analysis revealed that children's PM performance was the lowest compared to all other age groups (all ps < .001). In addition, PM performance of young adults was significantly better than that of middle-aged adults ($p < .001$) but not adolescents ($p = .97$). Adolescents and middle-aged adults did not differ in their performance ($p = .11$). There was also a significant main effect of encoding condition, F (2, 361) = 12.08, $p < .001$, $\eta_p^2 = .06$. Further Tukey tests indicated that participants in the EE condition outperformed participants in the EFT condition ($p = .004$) and controls ($p < .001$). There were no differences between the EFT and the standard encoding condition ($p = .22$). There was no significant interaction between PM cue and age group, F (3, 361) = 2.47, $p = .06$, $\eta_p^2 = .02$, or PM cue and encoding condition, F (2, 361) = 1.22, $p = .28$, $\eta_p^2 = .007$. No interaction between PM cue, age group and encoding condition was found, F (6, 361) = .76, $p = .60$, $\eta_p^2 = .01$.

As a robustness check, we additionally conducted a trial-level binomial logistic generalised linear mixed model (GLMM) to account for the discrete nature of the PM data and the nesting of repeated trials within individuals. The binary PM outcome (correct vs. incorrect) was modelled using a binomial distribution with a logit link function. Age group, encoding condition, PM cue, and all corresponding interaction terms were entered as fixed effects, and random intercepts were included for participants. The model was estimated using maximum likelihood with Laplace approximation. The analysis revealed significant main effects of age group, $\chi^2(3) = 56.93$, $p < .001$, and encoding condition, $\chi^2(2) = 11.56$, $p = .003$. No significant main effect of PM cue emerged, $\chi^2(1) = 0.79$, $p = .375$. Furthermore, the age group × encoding condition interaction, $\chi^2(6) = 9.68$, $p = .139$, the age group × PM cue interaction, $\chi^2(3) = 3.39$, $p = .335$, the encoding condition × PM cue interaction, $\chi^2(2) = 0.32$, $p = .852$, and the three-way interaction, $\chi^2(6) = 3.66$, $p = .723$, were not significant. Consistent with the ANOVA results, participants in the EE condition showed higher odds of correct PM performance than participants in the control condition ($OR = 2.95$, 95% CI [1.57, 5.54], $p < .001$), whereas the EFT and control conditions did not differ significantly ($OR = 1.44$, 95% CI [0.78, 2.67], $p = .241$). Thus, the GLMM yielded the same substantive conclusions as the primary ANOVA analyses (Figure 2).

Ongoing task performance

A 4 × 3 two-way ANOVA was conducted to analyze the effects of age group (children, adolescents, young adults, middle-aged adults) and encoding condition (EFT, EE, control condition) on ongoing task performance and revealed a significant main effect of age group, F (3,361) = 152.39, $p < .001$, $\eta_p^2 = .56$. Children showed the worst ongoing task performance compared to all other age groups (all ps < .001), whereas the other three age groups did not differ from one another (all ps > .90). There was no difference in ongoing task performance between adolescents and middle-aged adults ($p = .99$). There was no significant main effect of encoding condition, F (2,361) = 1.21, $p = .30$, $\eta_p^2 = .01$, indicating that the use of encoding strategies did not influence individuals' ongoing task performance. Furthermore, there was

Table 3. Means and standard deviations of PM, ongoing task performance, and time monitoring in the Mainz Garbage Truck across age groups and conditions, as well as pre-experience and vividness ratings in the EFT condition.

	N	Event-based PM *M* (*SD*)	Time-based PM *M* (*SD*)	Ongoing task *M* (*SD*)	Absolute monitoring *M* (*SD*)	Strategic monitoring T1 *M* (*SD*)	Strategic monitoring T2 *M* (*SD*)	Strategic monitoring T3 *M* (*SD*)	Pre-experience *M* (*SD*)	Vividness *M* (*SD*)	Total collected bins *M* (*SD*)
Children											
EFT	30	1.8 (1.3)	1.3 (1.1)	.71 (.08)	6.3 (4.9)	1.9 (1.2)	1.6 (1.5)	2.8 (2.9)	3.7 (1.2)	3.7 (1.2)	191.3 (20.4)
EE	29	2.6 (1.2)	1.4 (1.3)	.67 (.09)	7.7 (6.5)	2.2 (1.3)	2.1 (1.9)	3.4 (4.0)			185.9 (17.3)
Control	31	1.5 (1.2)	.90 (.98)	.67 (.09)	5.9 (3.2)	2.1 (1.2)	1.9 (1.3)	1.9 (1.8)			185.8 (15.9)
Adolescents											
EFT	32	3.7 (1.3)	2.8 (1.4)	.84 (.05)	10.2 (5.0)	2.2 (1.3)	2.6 (1.7)	5.4 (3.2)	3.5 (1.1)	3.8 (1.1)	206.5 (12.0)
EE	32	3.7 (1.1)	3.0 (1.2)	.85 (.04)	12.3 (5.0)	2.6 (1.7)	3.2 (1.5)	6.4 (3.8)			204.7 (17.0)
Control	32	3.6 (1.2)	3.2 (1.3)	.84 (.05)	11.5 (5.4)	1.8 (0.9)	3.0 (1.6)	6.6 (3.5)			207.1 (15.9)
Young adults											
EFT	33	3.5 (1.2)	3.0 (1.3)	.85 (.04)	14.1 (8.0)	2.8 (1.8)	4.0 (3.2)	7.3 (5.7)	3.5 (1.0)	3.8 (0.8)	218.8 (20.5)
EE	32	3.9 (1.2)	3.7 (1.1)	.85 (.05)	15.8 (8.2)	2.5 (1.4)	4.4 (3.4)	9.0 (5.3)			220.8 (24.1)
control	32	3.2 (1.3)	3.1 (1.3)	.84 (.05)	16.0 (8.5)	3.5 (4.0)	4.7 (3.7)	7.8 (4.5)			220.8 (26.1)
Middle-aged adults											
EFT	30	3.2 (1.5)	2.7 (1.3)	.84 (.06)	12.4 (6.3)	2.8 (1.9)	3.4 (2.2)	6.2 (4.7)	3.5 (1.1)	3.7 (0.8)	205.4 (22.1)
EE	30	3.7 (1.4)	3.4 (1.4)	.84 (.06)	12.8 (4.8)	2.4 (1.5)	3.5 (1.9)	6.9 (3.3)			205.4 (24.5)
Control	30	2.5 (1.5)	2.3 (1.3)	.84 (.05)	10.0 (6.1)	2.5 (1.7)	3.0 (2.2)	4.4 (3.7)			205.4 (24.5)

Note: EFT: episodic future thinking; EE: enactment encoding.

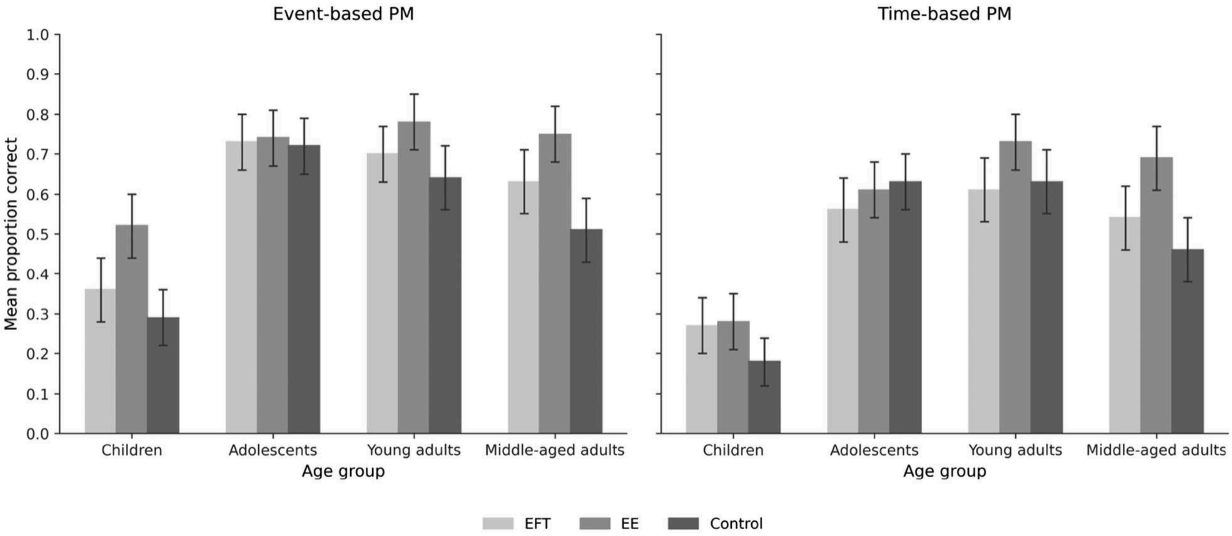

Figure 2. Mean PM performance by age group and encoding condition for event-based and time-based PM. Error bars represent 95% confidence intervals.

also no significant interaction between age-group and encoding condition, F (6,361) = .84, p = .54, η_p^2 = .01.

To examine whether the ongoing-task accuracy results might reflect a speed–accuracy trade-off, we additionally analysed the total number of collected bins as a proxy for task pace. Descriptive statistics are reported in Table 3. A 4 (age group) × 3 (encoding condition) ANOVA revealed a significant main effect of age group, F(3, 361) = 39.57, p < .001, η_p^2 = .25. Post hoc Tukey tests showed that children collected fewer bins than adolescents, young adults, and middle-aged adults (all ps < .001). Furthermore, young adults collected more bins than both adolescents and middle-aged adults (both ps < .001), whereas adolescents and middle-aged adults did not differ (p = .99). However, neither the main effect of encoding condition, F(2, 361) = 0.01, p = .995, η_p^2 < .001, nor the interaction between age group and encoding condition, F(6, 361) = 0.48, p = .821, η_p^2 = .01, was significant.

Task monitoring

To assess individuals' absolute fuel level monitoring during the Mainz Garbage Truck task another 4 (age group: children, adolescents, young adults, middle-aged adults) x 3 (encoding condition: EFT, EE, control condition) ANOVA was conducted and revealed a significant main effect of age group, F (3,361) = 30.64, p < .001, η_p^2 = .20, but no effect of encoding condition, F (2,361) = 1.99, p = .14, η_p^2 = .01 or interaction, F (6,361) = .82, p = .56, η_p^2 = .01. Across age groups, children showed the lowest (all ps < .001) and young adults the highest level of fuel monitoring (all ps < .001) compared to all other age groups. Adolescents and middle-aged adults showed comparable fuel monitoring (p = .98).

In addition, to assess individuals' strategic monitoring across the three time intervals of the time-based Mainz Garbage Truck task, a 4 (age group: children, adolescents, young adults, middle-aged adults) × 3 (encoding condition: EFT, EE, control condition) × 3 (time interval: 1–15 s, 16–30 s, 31–45 s) mixed ANOVA was conducted, with time interval as a within-subject factor. Descriptive statistics are presented in Table 3. Because Mauchly's test indicated that the assumption of sphericity was violated, Greenhouse–Geisser-corrected values are reported for effects involving time interval. The analysis revealed a significant main effect of time interval, F (1.37, 494.35) = 186.91, p < .001, η_p^2 = .34, indicating that strategic monitoring increased across the three time intervals. Pairwise comparisons showed that participants monitored significantly more often in the 16–30 s interval than in the 1–15 s interval and significantly more often in the 31–45 s interval than in both earlier intervals (all ps < .001). There was also a significant main effect of age group, F (3, 361) = 30.63, p < .001, η_p^2 = .20, but no effect of encoding condition, F (2, 361) = 1.97, p = .14, η_p^2 = .01, and no interaction between age group and encoding condition, F (6, 361) = .81, p = .56, η_p^2 = .01. Across time intervals, children showed the lowest level of strategic monitoring compared to all other age groups (all ps < .001), whereas young adults showed the highest level compared to all other age groups (all ps < .001). Adolescents and middle-aged adults showed comparable levels of strategic monitoring (p = .98). In addition, the effect of time interval differed across age groups, F (4.11, 494.35) = 14.84, p < .001, η_p^2 = .11, and across encoding conditions, F (2.74, 494.35) = 2.82, p = .043, η_p^2 = .02. The three-way interaction between time interval, age group, and encoding condition was not significant, F (8.22, 494.35) = 1.20, p = .30, η_p^2 = .02. Follow-up comparisons for the age group × time interval interaction indicated that in the first interval (1–15 s), children and young adults differed significantly (p = .002), and young adults also monitored more often than adolescents

($p = .009$), whereas the remaining comparisons were not significant. In the second interval (16–30 s), children monitored less often than all other age groups (all $ps \leq .002$), young adults monitored more often than adolescents and middle-aged adults (both $ps \leq .001$), and adolescents and middle-aged adults did not differ ($p = .29$). In the third interval (31–45 s), children monitored less often than all other age groups (all $ps < .001$), and young adults monitored more often than adolescents and middle-aged adults (both ps = .001), whereas adolescents and middle-aged adults again did not differ ($p = .58$). Follow-up comparisons for the encoding condition × time interval interaction showed no differences between encoding conditions in the first (all $ps \geq .70$) or second interval (all $ps \geq .18$). In the final interval (31–45 s), however, participants in the EE condition monitored significantly more often than those in the control condition ($p = .014$), whereas the EFT condition did not differ significantly from either the EE condition ($p = .052$) or the control condition ($p = .61$).

Correlational analysis

Pearson correlations were conducted to explore the relationships between PM and executive functions separately for each age group (see Table A1 to A4 in the Appendix). Results revealed a significant association between event-based PM performance and inhibition in children ($r = -.27$, $p < .05$), indicating that children who performed better in event-based PM tasks also showed better inhibitory control (CAVE: the lower the Stroop Score, the better the inhibitory control). Working memory was linked to both inhibition and switching (both $r = -.30$, $p < .001$), implying that enhanced working memory was related to better inhibitory control and switching (CAVE: the lower the switching scores, the better the individual's performance). There was also a significant relationship between planning in the 3-disk-version and planning in the 4 disk-version ($r = .40$, $p < .001$), as well as between planning (3-disk) and episodic memory ($r = -.28$, $p < .05$). In adolescents, no link was found between PM performance and executive functions. In young ($r = -.29$, $p < .001$) and middle-aged adults ($r = -.21$, $p < .05$), results revealed that time-based PM was associated with inhibitory control, indicating that for both, young and middle-aged adults, better time-based PM also linked to better inhibition. Additionally, in young adults, better event-based PM was associated with better switching ($r = -.22$, $p < .05$). For young and middle-aged adults, working memory significantly correlated with both inhibition (young adults: $r = -.32$, $p < .001$; middle-aged adults: $r = -.29$, $p < .001$) and switching (young adults: $r = .20$, $p < .05$; middle-aged adults: $r = -.29$, $p < .001$), indicating that participants who showed better working memory also demonstrated better inhibition and switching. Regarding young adults, planning in the 3-disk-version correlated with planning in the 4-disk-version ($r = .22$, $p < .05$). In middle-aged adults, participants' planning performance (4-disk) was associated with switching ($r = .25$, $p < .05$) and episodic memory ($r = -.31$, $p < .001$). Also, episodic memory and working memory were interrelated ($r = -.23$, $p < .05$). Finally, across all age groups better event-based PM performance was associated with better time-based PM performance (children: $r = .55$, $p < .001$; adolescents: $r = .22$, $p < .05$; young adults: $r = .36$, $p < .001$; middle-aged adults: $r = .34$, $p < .001$).

To further characterise engagement with the EFT manipulation, we also examined the associations between pre-experience, vividness, and PM performance per age group. Descriptive statistics are presented in Table 3. Neither self-rated pre-experience nor vividness was significantly correlated with PM performance.

Gaming experience

Figure 3 illustrates the relative frequencies of gaming experience in Jump'n'Run games in the different age groups. We performed correlational analyses for each age group to examine the relationship between time-based and event-based PM and gaming experience in Jump'n'Run games as well as total years of electronic gaming experience. Results revealed that more Jump'n'Run gaming experience was associated with better event-based ($r = .22$, $p < .05$) and time-based PM performance ($r = .23$, $p < .05$) in middle-aged adults. In young adults event-based PM performance was associated with lifetime electronic gaming experience ($r = .26$, $p < .001$). However, no correlations were observed in children and adolescents (all r's $< .07$). For further information regarding gaming experience across all age groups, see Figures A1–A4 in the Appendix.

Discussion

Forgetting to remember delayed intentions is a widespread problem across the entire lifespan and can cause severe problems with regards to academic goal achievement, maintaining an independent life or social relationships (Ellis & Freeman, 2008; Haas et al., 2020; Smith et al., 2000). There is evidence that providing individuals with an encoding strategy at the time of intention formation can help increase the likelihood of successful intention realisation. Thus, the present study aimed to explore the impact of two different encoding strategies (EFT – mental practice vs. EE – physical practice) during intention formation on the execution of delayed intentions in four different age groups (children, adolescents, young and middle-aged adults) compared to standard encoding. Participants were either asked to mentally simulate executing the PM and ongoing task (EFT condition) on the computer, physically perform actions related to executing the PM and ongoing task in everyday life (EE condition) or received standard instructions (no additional encoding strategy). To measure PM performance, a novel computerised game was used that asked participants to drive a

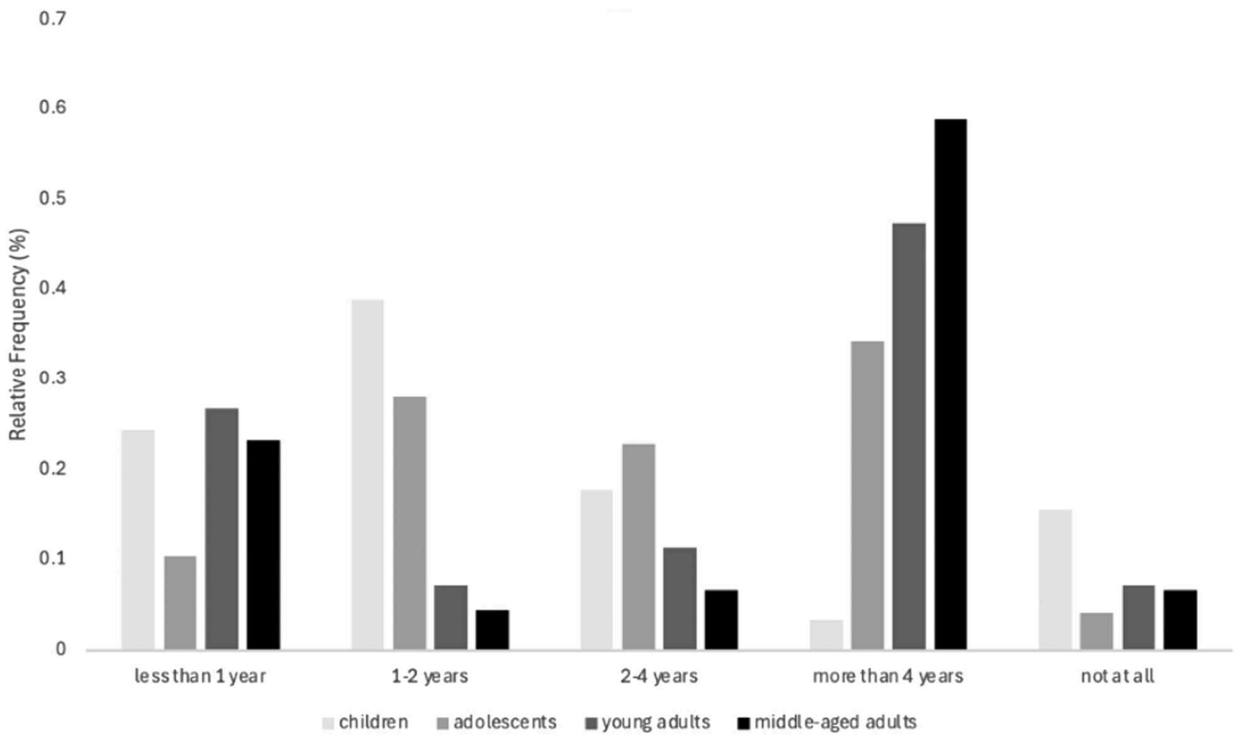

Figure 3. Relative frequency of self-reported Jump'n'Run gaming experience across age groups.

garbage truck on a road while remembering to execute embedded PM tasks (Mainz Garbage Truck).

Overview of results

As expected and in line with previous findings (Kliegel et al., 2008; Kretschmer-Trendowicz & Altgassen, 2016; Mattli et al., 2014; Stelz & Altgassen, 2025; Zimmermann & Meier, 2006), we found support for an inverted U-shaped development of PM performance, with children showing the lowest number of remembered delayed intentions, followed by adolescents and middle-aged adults and the best performance in young adults. However, the age composition of the middle-aged group should be kept in mind when interpreting this pattern, as participants in this group ranged from 30 to 55 years and thus represented a relatively young middle-adult sample. The findings should therefore not be generalised to later middle adulthood without caution. Similarly, with respect to individual differences, in line with our hypotheses and previous empirical results we found age-related differences in all examined executive functions (switching, working memory, inhibition, planning; Best & Miller, 2010; Zelazo et al., 2004) as well as for episodic memory (Shing et al., 2010). Overall, children showed the lowest performance, followed by adolescents and then middle-aged adults, while young adults performed best. Furthermore, as hypothesised, overall participants completed more event-based than time-based intentions in the Mainz Garbage Truck task. This finding is in line with previous evidence (Altgassen et al., 2015; Cheie et al., 2021; Stelz & Altgassen, 2025) and likely due to the assumed higher demands of time-based PM tasks on cognitive resources (e.g., attention, executive function) needed to remember and initiate the delayed intention given the absence of external cues indicating the appropriate moment to implement the task. This interpretation is also supported by the monitoring analyses. Across all groups, fuel checks increased significantly across the three successive time intervals within the 45-s cycle, indicating that participants adjusted their monitoring behaviour strategically as the critical target time approached. At the same time, children showed the lowest and young adults the highest levels of strategic monitoring, suggesting that age-related differences in time-based PM may partly reflect developmental differences in strategic time monitoring. Thus, the novel PM paradigm used in the present study (i.e., the Mainz Garbage Truck) replicated previous findings (e.g., Kerns, 2000; Voigt et al., 2011). Importantly, with regard to the effects of encoding strategies, we found a significant main effect of encoding condition, indicating overall differences between the three encoding conditions.

Effects of enactment encoding

Regarding EE, the overall analysis indicated that participants in the EE condition outperformed those in both the EFT and standard encoding conditions. Because no significant interaction with age group emerged, age-specific differences were interpreted descriptively rather than inferentially. Inspection of the means in Table 3 suggest that descriptively larger EE advantages were observed in children and middle-aged adults, whereas differences between encoding conditions appeared smaller in adolescents and young adults. This descriptive pattern is broadly in line with previous studies suggesting that EE during intention formation may support PM performance (Faustmann & Altgassen, 2024; Li & Wang, 2015; Passolunghi et al., 1995). In addition, EE did not affect ongoing task performance or task monitoring, suggesting that its beneficial effects on PM were not accompanied by clear changes in these concurrent task measures. Furthermore, participants in the three encoding conditions collected a comparable number of bins, providing no evidence for differences in task pace. Thus, the observed PM advantage in the EE condition is unlikely to be explained by a speed–accuracy trade-off. One possible explanation is that children and middle-aged adults also showed comparatively lower executive function and episodic memory performance. Physically enacting an intention at encoding may have been especially helpful in these groups by strengthening cue–action associations and supporting later retrieval under relatively higher cognitive demands, although the underlying mechanism cannot be determined from the present data. Moreover, the corresponding action for the event-based task that had to be performed as part of EE (i.e., dragging an imaginary garbage can behind oneself while walking three steps) caused great surprise in children (and laughter), which may have further strengthened cue–action associations. In terms of practical implications, the overall EE effect, together with the descriptive pattern in children, suggests that enriched encoding may be a promising avenue for supporting PM in everyday life. While children typically receive instructions verbally or in writing (similar to the standard encoding condition in this study), incorporating additional modalities into encoding, such as physical enactment, may improve their ability to remember to carry out planned actions. Future studies should explore whether combining multiple encoding modalities during intention formation could lead to even stronger effects in children. The descriptive pattern further raises the possibility that EE may also be useful in age groups showing some decline in PM performance, such as the present middle-aged sample or even older age groups. However, this interpretation requires further confirmation in future studies.

By contrast, descriptive differences between encoding conditions appeared to be smaller in adolescents and young adults. To our knowledge, this is the first study to assess the effects of EE on PM performance in adolescents, whereas several studies in young adults have reported beneficial effects of EE (Li et al., 2022; Pereira et al., 2012a, 2012b). As adolescents and young adults showed the best performance in executive functions and episodic memory, the impact of EE might not have been sufficient to improve an already well-established PM performance within these age groups. However, what may argue against this interpretation is that adolescents and young adults did not show any ceiling effects in their PM performance, so future research is needed to explain the lack of effects of EE. Moreover, we observed that especially adolescents, but also some young adults, appeared to feel self-conscious when they had to enact the related actions in front of the experimenter (e.g., embarrassed giggling), which may also have reduced the beneficial effects of EE.

Our study was the first to examine the impact of EE on time-based PM performance in children and adolescents. In the overall analysis, we found no evidence that the effect of EE differed systematically between event-based and time-based PM. Descriptively, however, several groups showed numerically higher time-based PM performance in the EE condition, with the clearest mean advantage emerging in the middle-aged adults. This pattern is broadly in line with Faustmann and Altgassen (2024), who reported beneficial effects of EE specifically for time-based PM. Unlike our study, however, Faustmann and Altgassen (2024) asked participants to perform exact corresponding actions in the EE condition, whereas we used symbolically corresponding actions. Future studies should therefore explore different forms of EE to determine the most effective approach. One possible explanation is that physically practicing a time-based intention may be more difficult than practicing an event-based one, which typically has a stronger contextual and semantic connection and may therefore more readily lend itself to a corresponding action. The physical action associated with the time-based task (refuelling) lacked crucial temporal information, necessitating continued strategic monitoring for successful task completion and thus possibly failing to support the process most critical for time-based PM. This interpretation is broadly consistent with the monitoring results, which showed that strategic monitoring increased toward the final time interval of the 45-s cycle across groups. Although EE did not affect absolute task monitoring, a small encoding condition × time interval interaction emerged, suggesting that participants in the EE condition monitored somewhat more frequently than those in the control condition in the final interval. Given the small size of this effect and the absence of a general encoding effect on strategic monitoring, however, this pattern should be interpreted cautiously and should not be overinterpreted as a mechanism underlying the PM advantage in the EE condition. Future research should examine the effects of EE on time-based PM tasks that more directly incorporate time monitoring into the encoding phase.

Impact of EFT on PM performance

Regarding the impact of EFT on PM performance, we did not find the hypothesised beneficial effect of EFT on the realisation of delayed intentions in any of the examined age groups. Although most previous studies reported improved PM performance following EFT during intention formation (Altgassen et al., 2015, 2017 – only for adolescents; Brewer & Marsh, 2010; Kretschmer-Trendowicz et al., 2016, 2019; Li et al., 2022; Ma & Zhang, 2024; Neroni et al., 2014; Nigro et al., 2014; Passolunghi et al., 1995), null findings have also been reported across different age groups (Altgassen et al., 2017 – no effect for young adults; Cottini et al., 2021 – no effect for children aged 8–11 years; Faustmann & Altgassen, 2024 – no effect for adults). Thus, the present findings do not stand entirely in isolation, but rather suggest that EFT benefits may depend on specific task and age-related conditions.

In children, the absence of an EFT benefit is consistent with Cottini et al. (2021), despite differences in the exact EFT instructions used. While some studies have suggested that EFT may improve children's PM performance (e.g., Kretschmer-Trendowicz et al., 2016; Kretschmer-Trendowicz et al., 2019), our results indicate that EFT may remain a cognitively demanding strategy for this age group, particularly under conditions of relatively high ongoing task demands. In addition, the brief EFT phase used here (approximately 5–7 min) may have been insufficient, especially for children, to establish a stable benefit (Cottini et al., 2021). More generally, it remains unclear how still-developing cognitive and metacognitive abilities affect children's capacity to apply EFT effectively. In adolescents and young adults, one possible explanation is that externally imposed EFT instructions may have interfered with spontaneously used encoding strategies rather than providing an additional benefit (Altgassen et al., 2017). This interpretation may also help explain why no clear EFT effect emerged in young adults in the present study. Similarly, Faustmann and Altgassen (2024) did not find beneficial effects of EFT in their healthy control group of middle-aged adults.

At the task level, one possible explanation for the null findings is that the Mainz Garbage Truck may have provided relatively unfavourable conditions for EFT. In the event-based PM task, the cues were not focal to the ongoing task, as participants primarily had to process lane position and garbage-can collection rather than the houses at the roadside. According to the Multiprocess Framework (McDaniel & Einstein, 2000), EFT may be more likely to support PM when delayed intentions can later be triggered by focal cues and more spontaneous retrieval. Although the event-based cues were not focal to the ongoing task, their colour contrast may have increased their visual salience. At the same time, the present findings suggest that this salience may not have been sufficient to outweigh the demands imposed by the high ongoing task absorption and cue non-focality. In addition, the ongoing task may have been particularly engaging and resource demanding, requiring participants to steer across three lanes, collect the correct garbage cans, avoid incorrect ones, and avoid construction sites. Such high ongoing task absorption may have increased cognitive load and reduced the extent to which participants were able to benefit from EFT.

For the time-based PM task, a further limitation of the EFT manipulation is that participants were not explicitly instructed to incorporate time monitoring into their visualisation. Given that strategic time monitoring is particularly important for time-based PM (Einstein & McDaniel, 1996), this omission may also have reduced the potential benefit of EFT. Finally, the null findings may reflect the relative unfamiliarity of the task intentions, particularly for adult participants. EFT may be less effective when intended actions are harder to imagine on the basis of prior experience. Future research should therefore examine EFT effects across tasks that vary more systematically in cue focality, cognitive absorption, and subjective familiarity.

With regard to the generalizability of the present findings, several limitations should be taken into account. As the study did not include older adults, it remains unclear to what extent the observed pattern would extend to old adulthood, particularly given potential age-related differences in computer-game familiarity. In addition, the Mainz Garbage Truck represents a specific, game-based PM context, and the findings may therefore not directly generalise to other ecological conditions, such as everyday PM situations in which external reminders are common or in which intended actions are more familiar and personally relevant.

Conclusion

In conclusion, the present findings suggest that EE can support PM performance, whereas EFT did not yield comparable benefits in the present paradigm. This points to the potential value of action-based encoding support, particularly in age groups with comparatively lower PM performance. At the same time, the findings underline that the effectiveness of encoding strategies depends on the specific task context. Future research should clarify the mechanisms underlying the EE effect and identify the conditions under which different encoding strategies are most beneficial across development.

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Appendix

Table A1. Correlational analysis between PM and executive functions in children.

	Event-based PM	Inhibition	Switching	Working memory	Planning (3-disk)	Planning (4-disk)	Episodic memory
Time-based PM	.55**	−.06	−.16	−.07	.05	.08	.02
Event-based PM		−.27*	−.07	−.05	−.12	.02	.01
Inhibition			.17	−.30**	.04	−.16	−.04
switching				−.30**	.07	.08	−.17
Working memory					−.07	.16	.25*
Planning (3-disk)						.40**	−.28**
Planning (4-disk)							−.03

Note: * = $p < .05$, ** = $p < .001$.

Table A2. Correlational analysis between PM and executive functions in adolescents.

	Event-based PM	Inhibition	Switching	Working memory	Planning (3-Disk)	Planning (4-disk)	Episodic memory
Time-based PM	.22*	.03	−.04	.08	.08	.06	−.13
Event-based PM		.05	.15	−.01	−.09	−.02	−.04
Inhibition			.09	−.15	−.06	−.03	−.01
Switching				−.18	.02	.13	−.19
Working memory					−.09	−.10	−.09
Planning (3-disk)						.11	−.01
Planning (4-disk)							.10

Note: * = $p < .05$, ** = $p < .001$.

Table A3. Correlational analysis between PM and executive functions in young adults.

	Event-based PM	Inhibition	Switching	Working memory	Planning (3-disk)	Planning (4-disk)	Episodic memory
Time-based PM	.36**	−.29**	.10	.12	−.13	.04	.07
Event-based PM		.06	−.22*	.13	−.14	.04	−.01
Inhibition			.09	−.32**	.00	.00	−.14
Switching				−.20*	−.01	.03	−.07
Working memory					.07	−.09	.07
Planning (3-disk)						.22*	−.04
Planning (4-disk)							.06

Note: * = $p < .05$, ** = $p < .001$.

Table A4. Correlational analysis between PM and executive functions in middle-aged adults.

	Event-based PM	Inhibition	Switching	Working memory	Planning (3-disk)	Planning (4-disk)	Episodic memory
Time-based PM	.34**	−.21*	−.02	.17	.21	−.13	.15
Event-based PM		−.20	−.15	.19	.05	−.02	.14
Inhibition			.13	−.29**	.07	.14	−.10
Switching				−.29**	−.07	.25*	−.31**
Working memory					−.02	−.13	.23*
Planning (3-disk)						−.02	−.11
Planning (4-disk)							−.09

Note: * = $p < .05$, ** = $p < .001$.

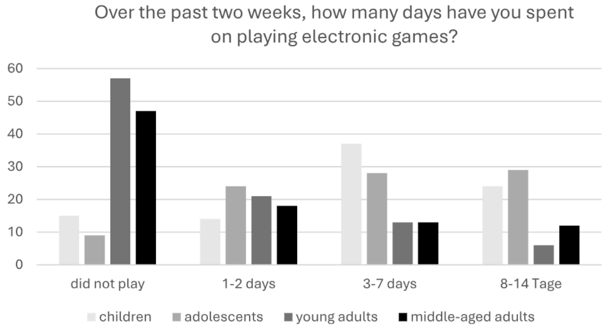

Figure A1. Number of days participants engaged in electronic gaming over the last two weeks.

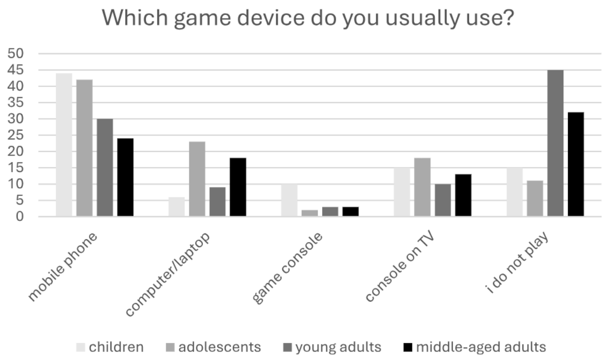

Figure A2. Most frequently used game device.

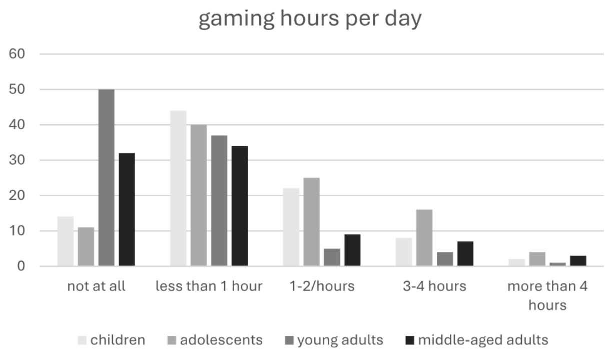

Figure A3. Gaming hours per day across all age groups.

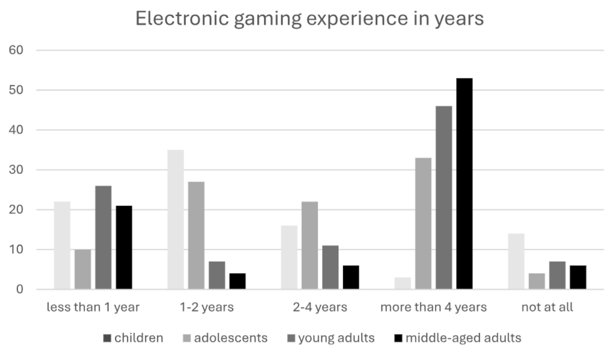

Figure A4. Participants electronic gaming experience in years across age groups.