Effects of Task Characteristics and Individual Characteristics on Prospective Memory Aftereffects and Their Mechanisms

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Abstract

Aftereffects of prospective memory refer to the phenomenon where individuals erroneously repeat executing completed prospective memory intentions or where completed intentions interfere with ongoing tasks. Based on the multiprocess theory of prospective memory, a literature review reveals that task characteristics (prospective memory task characteristics, ongoing task characteristics, task context) and individual characteristics modulate event-based prospective memory aftereffects. Currently, theoretical explanations for the processing mechanisms of event-based prospective memory aftereffects mainly include automatic processing, controlled processing, retrieval-inhibition processing, stop-tag processing, dual-process, and dynamic multiprocess, among others. Among these, automatic processing can be divided into reflexive-associative processing and discrepancy-search processing, while controlled processing can be further divided into monitoring processing and inhibitory processing. The formation of event-based prospective memory aftereffects is more closely related to automatic processing and monitoring processing, whereas the attenuation of aftereffects relies more heavily on inhibitory processing. Future research should thoroughly investigate the processing mechanisms of event-based prospective memory aftereffects, increase examinations of aftereffects in different types and natural contexts, and focus on exploring strategies to reduce prospective memory aftereffects.

Effects of Task and Individual Characteristics on the Aftereffects of Event-Based Prospective Memory and Their Mechanisms

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Abstract: The aftereffects of prospective memory (PM) refer to the phenomenon where individuals erroneously repeat an already completed PM intention (commission errors) or where completed intentions interfere with ongoing task performance. Based on the multiprocess theory of PM, a review of the literature reveals that task characteristics (PM task characteristics, ongoing task characteristics, task context) and individual traits modulate the aftereffects of event-based PM. Current theoretical explanations for the processing mechanisms underlying these aftereffects include automatic processing, controlled processing, extraction-inhibition processing, stop-tag processing, dual processing, and dynamic multiprocess frameworks. Among these, automatic processing can be subdivided into reflexive-associative processing and discrepancy-plus-search processing, while controlled processing can be divided into strategic monitoring and inhibitory processing. The formation of event-based PM aftereffects is more closely related to automatic and strategic monitoring processes, whereas the deactivation of such aftereffects depends more heavily on inhibitory processing. Future research should further investigate the processing mechanisms of event-based PM aftereffects, expand examinations of aftereffects across different PM types and naturalistic contexts, and focus on developing strategies to reduce PM aftereffects.

Keywords: aftereffects of prospective memory, task characteristics, individual traits, automatic processing, controlled processing

In daily life, we often need to remember to perform future events or activities. This future-oriented memory is called prospective memory (PM), defined as remembering to execute a planned event or activity at an appropriate time or in an appropriate situation in the future (Einstein & McDaniel, 1990). PM is typically divided into event-based PM and time-based PM. Event-based PM involves clear external cues, whereas time-based PM lacks obvious external cues and relies more on internal self-monitoring.

Some studies suggest that intention representations at least partially deactivate after PM task completion (Matos & Albuquerque, 2021b; Schaper & Grundgeiger, 2019; Walser, Plessow, et al., 2014). However, the vast majority of research consistently demonstrates that PM intentions are not fully deactivated after completion, leading to PM aftereffects (Bugg & Streeper, 2019; Cottini & Meier, 2020; Matos & Albuquerque, 2021a; Matos et al., 2020; Meier & Cottini, 2023; Möschl et al., 2020; Streeper & Bugg, 2021). For example, patients who must take daily medication may repeat doses because they forget they have already taken the prescribed amount. When medications have severe side effects, overdosing can seriously impact health (Kimmel et al., 2007). This phenomenon is known as PM aftereffects, which refers to the erroneous repetition of completed PM intentions (commission errors) or interference from completed intentions on ongoing task performance (Bugg et al., 2016; Cottini & Meier, 2020; Matos & Albuquerque, 2021a; Meier & Cottini, 2023; Meier & Rey-Mermet, 2012, 2018; Möschl et al., 2020; Walser et al., 2017; Walser, Plessow, et al., 2014; Xin et al., 2022; 郭云飞等, 2019; 辛聪等, 2019; 辛聪等, 2020; 周晨琛等, 2020).

Dual-process or multiprocess theory posits that PM processing involves both automatic and controlled processing (McDaniel & Einstein, 2000; Scullin et al., 2013). Automatic processing does not consume cognitive resources and involves spontaneous retrieval when encountering target cues. Controlled processing, in contrast, consumes cognitive resources as individuals must continuously monitor target cues and potential contexts. This theory suggests that various factors determine whether PM processing consumes more cognitive resources, including task characteristics (PM task and ongoing task features) and individual traits (Einstein & McDaniel, 2005; Einstein et al., 2005; McDaniel & Einstein, 2000; Scullin et al., 2013). Although this theory was developed for the PM activation phase, the activation and completion phases are closely related, and factors affecting PM performance during activation may also influence completed PM intentions (Matos & Albuquerque, 2021a; Möschl et al., 2020). While some researchers have examined how PM tasks, ongoing tasks, and individual characteristics affect event-based PM aftereffects (Bugg & Scullin, 2013; Cottini & Meier, 2020; Matos & Albuquerque, 2021b; Matos et al., 2020; Meier & Cottini, 2023; Pink & Dodson, 2013; Schaper & Grundgeiger, 2017; Scullin et al., 2012; Scullin et al., 2011; Scullin et al., 2009; Walser, Goschke, et al., 2014; Walser et al., 2017), no study has systematically reviewed these influences. Moreover, previous reviews of the cognitive and neural mechanisms of event-based PM aftereffects have been insufficient, focusing primarily on either formation or deactivation (Matos & Albuquerque, 2021a; Möschl et al., 2020; 黄欢等, 2018) without detailing both processes comprehensively. Therefore, this paper will systematically introduce the various influences of task and individual characteristics on event-based PM aftereffects, further review the cognitive and neural mechanisms underlying their formation and deactivation, and finally summarize limitations of existing research and directions for future studies.

2.1.1 PM Task Characteristics

Task characteristics refer to general properties of tasks, such as task type. Research on event-based PM aftereffects includes both PM tasks and ongoing tasks, and their combined characteristics can be analyzed comprehensively. PM task characteristics mainly include PM cue features (salience, focality, semantic and perceptual cue types, number of cues, etc.) and PM task nature (habitual PM tasks, similarity between activation and completion phases, etc.). Research shows that PM cue features affect not only PM performance during activation but also the magnitude of PM aftereffects. Salient cues typically manipulate the specificity of PM cues to make them distinctly different from other stimuli. Most studies modify PM cue color, with non-salient cues usually being black or white to match ongoing task stimuli, while salient cues are typically red, making them visually distinct from ongoing task stimuli. Research indicates that salient cues, due to their "prominent" external visual features, facilitate spontaneous retrieval of PM intentions (Harrison et al., 2014; Kretschmer-Trendowicz & Altgassen, 2016; Smith et al., 2007). Scullin et al. (2012) systematically compared the effects of salient and non-salient cues on PM aftereffects, finding that salient cues produced more commission errors than non-salient cues. This may be because salient cues remain at a higher activation level during the completion phase, making spontaneous retrieval more likely and thereby increasing PM aftereffects.

Previous research has rarely distinguished between cue salience and focality, with most studies directly employing PM cues that are both salient and focal (Bugg & Scullin, 2013; Bugg et al., 2013; Bugg et al., 2016; Pink & Dodson, 2013; Scullin & Bugg, 2013; Scullin et al., 2011; Scullin et al., 2009). Beyond salient cues, focal cues also increase PM aftereffects (Hefer et al., 2017; Meier & Cottini, 2023; Meier & Rey-Mermet, 2018). Focality refers to whether the ongoing task promotes processing of critical features of PM cues; if it does, processing is focal, otherwise it is non-focal. Under focal processing conditions, ongoing task processing facilitates processing of target cue features, which involves automatic processing. Meier and Cottini (2023) used commission errors and reaction times to original PM cues and ongoing tasks as measures, finding that focal cues enhanced processing overlap between PM and ongoing tasks, leading to spontaneous retrieval of completed intentions and thereby increasing PM aftereffects.

Recent research shows that semantic and perceptual cue types modulate PM aftereffects. Unlike salient cues, perceptual cues do not necessarily have "prominent" external features and may be perceptually equivalent to ongoing task stimuli. Cottini and Meier (2020) randomly assigned participants to semantic or perceptual cue conditions. In the perceptual cue condition, participants performed specific key presses when encountering red or yellow objects, whereas in the semantic cue condition, they responded to objects belonging to animal or ship categories. Using commission errors and reaction times as measures, they found that semantic cues produced larger PM aftereffects than perceptual cues. They argued that semantic cues consume more cognitive resources and rely more heavily on strategic monitoring. During PM activation, monitoring strengthens associations between PM cues and intentions, and active monitoring increases PM aftereffects.

Bugg and Scullin (2013) manipulated the number of cues, finding that incomplete PM intention conditions (0 PM cues) produced greater PM aftereffects than completed intention conditions (4 PM cues). This can be explained by the

Zeigarnik effect, which states that unexecuted intentions are harder to forget than executed ones (Marsh et al., 1998; Zeigarnik, 1938). Therefore, compared to 4 cues, the 0-cue condition may maintain PM intentions at a higher activation level, making commission errors more likely and producing larger PM aftereffects. Multiple executions of PM intentions may yield two outcomes: (1) strengthening cue-intention associations, promoting spontaneous retrieval of completed PM intentions and causing aftereffects (McDaniel et al., 2009; Pink & Dodson, 2013); or (2) creating richer contextual traces or more robust intention completion representations, making it easier to form a “No-Go” memory. When cognitive resources are sufficient, inhibitory control can deactivate completed PM intentions, reducing aftereffects, which involves inhibitory processing (Bugg et al., 2016; Walser, Plessow, et al., 2014). Since prior execution facilitates deactivation, how does the number of cue presentations affect PM aftereffects? Walser and Plessow et al. (2014) manipulated the number of PM cue presentations during completion (4 or 12 times) and found that 12 presentations did not increase PM aftereffects. Multiple PM responses promoted deactivation of completed intentions, supporting the second outcome described above and better explained by inhibitory processing.

Researchers have primarily explained cue feature effects on PM aftereffects based on cue-intention association strength, which relates to how PM intentions are encoded. Manipulations of encoding methods primarily occur during the intention formation phase, using instructions to strengthen or weaken PM cue-intention associations. Compared to standard encoding, implementation intention encoding produces larger PM aftereffects (Bugg et al., 2013). Implementation intention encoding establishes strong cue-intention associations using “if-then” instructions. This strategy contains two components: the “if” component involves detecting the anticipated situation, while the “then” component automatically activates and executes the target behavior (Bugg et al., 2013; Zimmermann & Meier, 2010). This encoding strategy prompts individuals to mentally represent the situation and closely link it to behavioral responses, facilitating spontaneous retrieval of completed intentions and increasing PM aftereffects.

Beyond cue features, PM task nature also affects aftereffect magnitude. Most studies require participants to execute PM tasks multiple times during activation and then perform ongoing tasks when encountering original PM cues during completion. Habitual PM tasks involve establishing habitual stimulus-response associations through repeated specific responses to PM targets during activation, which promotes spontaneous retrieval of completed intentions and causes aftereffects. Multiple PM intention executions do not necessarily create habitual PM responses; compared to executing PM intentions only several or a dozen times, executing them dozens of times is more likely to produce habitual responses. Therefore, habitual PM tasks may lead to automatic processing of completed PM intentions and create richer intention completion representations that enable inhibitory processing. Since PM aftereffects are modulated by multiple factors (e.g., task load, individual executive control levels) that affect results, if habitual PM tasks show larger aftereffects than non-habitual tasks, automatic or dual-process explanations are more appropriate. If habitual PM shows smaller aftereffects, inhibitory processing explanations are more suitable. McDaniel et al. (2009) found that habitual PM tasks strengthened cue-intention associations, leading to higher commission errors. Similarly, Pink and Dodson (2013) manipulated PM task habituality and found that habitual conditions increased commission errors compared to non-habitual conditions. Habitual responses to PM cues formed during activation maintain completed intentions at high activation levels during completion, making spontaneous retrieval more likely and requiring higher-level inhibitory control for deactivation. Individuals typically show inhibitory failure, resulting in PM aftereffects.

Walser et al. (2017) investigated how similarity between activation and completion phase PM tasks affects aftereffects. The study created four conditions varying cue and response type similarity: both similar, both different, similar cues but different responses, and different cues but similar responses. Using commission errors and reaction times as measures, they found that only cue similarity between phases promoted spontaneous retrieval of completed PM intentions, causing larger aftereffects. PM aftereffects represent sustained activation of intention representation's stimulus component; cue similarity triggers automatic retrieval of the original PM cue's action component, rather than storing PM intention representations as specific cue-response associations. Since response type similarity did not affect aftereffect magnitude, representations of completed PM intentions may not be stored as specific cue-keypress associations (Walser et al., 2017).

2.1.2 Ongoing Task Characteristics

Beyond PM task characteristics, ongoing task characteristics also influence PM aftereffects. These include ongoing task load and matching between activation and completion phase ongoing tasks. If ongoing task cognitive load increases, cognitive resources available for inhibiting completed PM intentions decrease. When resources are insufficient, inhibitory failure occurs, leading to PM aftereffects. Some researchers have increased ongoing task cognitive load during completion, for example by adding tone-monitoring (Boywitt et al., 2015) or number-monitoring tasks (Pink & Dodson, 2013), finding that increased load enlarges PM aftereffects. Recently, Matos et al. (2020) added a counting recall task to an ongoing lexical decision task, requiring participants to count yellow screen presentations (medium load) or all colored screen presentations (high load). Using commission errors and reaction times as measures, they found that medium load produced larger aftereffects than no load, with no difference between medium and high load conditions. The absence of larger aftereffects under high load may be because cognitive load interfered with PM cue processing, preventing completed PM intentions from reaching conscious awareness. Given that significant aftereffects were not observed under high ongoing task load, the relationship between ongoing task load and PM aftereffects may be non-linear, meaning increased load does not necessarily increase aftereffects.

Previous research has rarely distinguished between activation and completion phase ongoing tasks, typically setting them as identical (Matos & Albuquerque, 2021a; Möschl et al., 2020; Scullin et al., 2011; Scullin et al., 2009). Scullin et al. (2012) found that matching between activation and completion phase ongoing tasks affects PM aftereffects. In the matching condition, both phases used lexical decision tasks, while in the non-matching condition, activation used graphic rating tasks and completion used lexical decision tasks. Results showed that matching conditions produced higher commission errors. Matching increases cognitive processing overlap between phases, promoting spontaneous retrieval of completed PM intentions. When encountering original PM cues during completion, inhibitory failure is more likely, causing PM aftereffects.

2.1.3 Task Context

Beyond PM and ongoing task characteristics, PM aftereffects also relate to task context, which refers to task-related settings and execution backgrounds. Specifically, task paradigms and background settings between activation and completion phases connect to aftereffect formation and deactivation. Laboratory research primarily uses two paradigms to assess event-based PM aftereffects: event-based PM paradigms with semantic associates of PM cues, and event-based PM paradigms with no-longer-relevant PM cues. The latter can be subdivided into three types: repetition error paradigm, repeated cycles paradigm, and commission errors paradigm (Matos & Albuquerque, 2021a; Möschl et al., 2020).

First, the semantic associates paradigm requires participants to retrieve picture combinations during picture rating tasks alternating with lexical decision tasks. After retrieving PM picture cue combinations, lexical decision reaction times for semantically related versus unrelated words are compared; similar or slower responses are interpreted as deactivation or inhibition of completed intentions (Förster et al., 2005). Second, the repetition error paradigm does not involve a PM completion phase; participants typically perform specific PM responses when PM cues first appear and different responses when cues reappear. Therefore, if participants make the original PM response when a cue appears again after correctly responding the first time, commission errors occur (Matos & Albuquerque, 2021a). Third, in the repeated cycles paradigm, participants complete multiple activation-completion cycles (Walser et al., 2012; Walser, Goschke, et al., 2014; Walser et al., 2017; Walser, Plessow, et al., 2014). After activation, participants are told the PM task is completed and only the ongoing task remains. After completion, a new activation-completion cycle begins with different PM cues. Aftereffects are assessed by comparing differences (reaction times, ongoing task errors, commission errors) between no-longer-relevant PM cues and baseline trials. Fourth, the commission errors paradigm requires participants to complete single activation and completion phases (Bugg & Scullin, 2013; Bugg et al., 2013; Bugg & Streeper, 2019; Scullin & Bugg, 2013; Scullin et al., 2012; Scullin et al., 2011). Participants are not required to respond only to the first PM cue appearance. During activation, participants perform ongoing tasks and specific responses to PM targets. During completion, no specific responses to original PM targets are required, only ongoing tasks. Aftereffects are reflected by responses to original PM targets or interference with ongoing tasks (Möschl et al., 2020). Schaper and Grundgeiger (2017) developed a delay-execute paradigm based on the commission errors paradigm to examine PM aftereffects. This paradigm requires a clear time delay between intention retrieval and execution. It differs from the commission errors paradigm in two key ways: first, only the delay-execute paradigm includes an obvious temporal pause between retrieval and execution; second, PM cues in the delay-execute paradigm are typically highly salient to ensure intention retrieval, whereas commission errors paradigms do not always use highly salient cues.

These paradigms differ substantially. For example, the semantic associates paradigm involves semantic networks related to cues or anticipated actions, which may be inhibited more quickly after intention completion. Paradigms with no-longer-relevant cues involve cue representations, anticipated actions, or stimulus-response associations that are more difficult to deactivate after completion (Möschl et al., 2020). Additionally, semantic associates and repetition error paradigms do not involve PM completion phases, whereas repeated cycles, commission errors, and delay-execute paradigms include both activation and completion phases. The repeated cycles paradigm requires constantly switching responses to formed PM intentions when measuring aftereffects, whereas the commission errors paradigm demands this ability less, and they differ in measurement indicators. In summary, paradigm differences may also affect aftereffect magnitude.

Beyond paradigms, temporal delay and task load between activation and completion phases relate to PM aftereffects. Over time and with interference from other memory content, intention representations may gradually deactivate after completion (Walser, Plessow, et al., 2014). Scullin et al. (2009, 2011) manipulated intervals before encountering original PM cues during completion by requiring participants to perform picture rating tasks containing either 80 trials (long delay) or 24 trials (short delay). Using reaction times to original PM cues and ongoing tasks as measures, they found no significant differences between delay conditions, suggesting time delay does not affect PM aftereffects. In contrast, Walser et al. (2012) found PM aftereffects gradually decreased with increasing delay. Similarly, Walser and Plessow et al. (2014) set two blocks containing original PM cues during completion and found slower responses only in the first block, with no differences in the second block, indicating aftereffects are less likely with long delays. Currently, conclusions about the relationship between temporal delay and PM aftereffects are inconsistent, possibly due to differences in paradigms, PM and ongoing task types, and delay interval settings. Walser et al. used the repeated cycles paradigm with perceptual cues (judging specific symbols) and a number parity ongoing task, with delays set across blocks. Scullin et al. primarily used the commission errors paradigm with semantic cues (judging specific words) and a lexical classification ongoing task, with delays involving picture rating tasks of varying lengths before completion—whether this creates interference or merely delay remains unclear.

Increasing task load between activation and completion phases also affects aftereffect magnitude. Walser and Goschke et al. (2014) manipulated task load between PM activation and completion phases and found that performing a more cognitively demanding task after activation reduced PM aftereffects compared to control conditions. Recently, Matos and Albuquerque (2021b) also investigated how inter-phase task load affects aftereffects. Participants completed a verbal comprehension task under no working memory load, and 1-back and 3-back tasks under low and high load conditions, respectively. Using reaction times to original PM cues and ongoing tasks as measures, they found both high and low load produced fewer aftereffects than no load. Deactivation of completed PM intentions depends on cognitive resources available before the completion phase begins. Immediately performing a moderate or high working memory load task after PM activation promotes deactivation of completed intentions.

2.2.1 Age

Beyond task characteristics, individual traits also influence PM aftereffects. Individual traits refer to characteristics and differences in physiology, psychology, and behavior. Numerous studies have examined age-related differences in PM aftereffects, finding close associations with cognitive aging (Boywitt et al., 2015; Bugg et al., 2013; Bugg 2011). Cottini and Meier (2020) first compared PM aftereffects across three age groups, finding that children monitored PM cues less than young and older adults during activation, but both children and older adults showed larger aftereffects than young adults during completion. Children's cognitive functions are still developing, making complete inhibition of completed intentions difficult (Cottini & Meier, 2020). Additionally, cognitive aging reduces inhibitory control, which is crucial for suppressing dominant responses and reducing interference from irrelevant stimuli. Compared to young adults, children and older adults have insufficient inhibitory control, making it difficult to suppress spontaneous retrieval of completed PM intentions during completion and easily forming PM aftereffects (Scullin et al., 2011; 辛聪等, 2019).

2.2.2 Executive Control and Output Monitoring

Executive control is a higher-order cognitive ability referring to top-down storage, planning, and manipulation of relevant information during information processing (Braver & Barch, 2002). Executive control ability negatively correlates with PM aftereffect magnitude (Scullin et al., 2012; Scullin et al., 2011). Scullin et al. (2012, 2011) measured executive control using Stroop tasks, Trail Making Tests, and Wisconsin Card Sorting Tasks, finding that higher executive control ability corresponded to less pronounced PM aftereffects. Output monitoring of completed PM intentions is a crucial factor in reducing aftereffects;

during completion, individuals must notice and recall that the original PM intention has been executed. Output monitoring refers to memory of whether an intended action has been completed (Ball et al., 2018; Skladzien, 2010), and output monitoring failure can lead to repetition or omission of planned actions. Ball et al. (2018) found that attentional control relates to output monitoring during PM activation, while output monitoring of completed intentions relates to episodic memory. Successful output monitoring occurs when participants judge that an original PM cue has previously appeared and correctly press a "repeat" key. Failure occurs when participants judge the cue as first appearing and incorrectly press a "first appearance" key (commission error) or fail to detect the original PM cue (miss). Results showed that regardless of attentional processing involved, once PM intentions are completed, output monitoring performance links to episodic information about original PM cues, and stronger output monitoring ability promotes deactivation of completed intentions.

2.2.3 Personality Traits

Action versus state orientation is considered a potential moderator of PM aftereffects (Penningroth, 2011). State orientation refers to the tendency toward indecisiveness and hesitation regarding new intentions, whereas action orientation involves immediately taking action and decisively initiating new intentions (Goschke & Kuhl, 1993). Kuhl and Beckmann (1994) propose that individuals may have stable action or state orientation tendencies that develop over time as personality traits. Research indicates that state-oriented individuals maintain intentions at higher activation levels more than action-oriented individuals and show more persistent searching for uncompleted intentions (Beckmann, 1994; Goschke & Kuhl, 1993). According to residual activation perspectives, PM tasks typically maintain higher activation levels than other memory contents, and when completed PM intentions remain highly activated, PM aftereffects occur (Walser et al., 2012). Walser and Goschke et al. (2014) used reaction times to original PM cues and ongoing tasks as measures, finding that state-oriented individuals produced larger PM aftereffects than action-oriented individuals. Slower responses to PM cues in state-oriented individuals may reflect elaborative processing that strengthens PM intention representations, making completed intentions harder to deactivate and producing larger aftereffects.

2.3 Summary

Regarding PM task characteristics, salient and focal cues and increased cue-intention association strength promote spontaneous retrieval of completed PM intentions, while semantic cues may promote sustained monitoring of completed intentions—both easily forming PM aftereffects. Compared to unexecuted intentions, executed intentions promote aftereffect deactivation. Reducing cue salience, focality, and cue-intention association strength facilitates deactivation, and perceptual cues promote deactivation more than semantic cues. Habitual PM tasks and similarity between activation and completion phase PM cue types typically promote automatic processing of completed PM intentions, making spontaneous retrieval difficult to inhibit and more likely to form aftereffects. Reducing PM task habituality and cue type similarity between phases may promote aftereffect deactivation.

Regarding ongoing task characteristics, high ongoing task cognitive load typically consumes more cognitive resources, leaving insufficient resources during completion to inhibit completed PM intentions, making aftereffects more likely. Matching between activation and completion phase ongoing tasks promotes spontaneous retrieval of completed intentions, requiring higher-level inhibitory control for deactivation. Individuals typically show inhibitory failure, causing PM aftereffects. Therefore, reducing ongoing task cognitive load allows limited resources to be used for deactivating completed intentions. Moreover, reducing matching between phases may decrease spontaneous retrieval and promote aftereffect deactivation.

Task context settings may also affect PM aftereffects, including paradigms and inter-phase settings. Currently, only speculation exists that paradigm differences may affect aftereffect magnitude, but which paradigms more effectively promote formation or deactivation requires further investigation. Deactivation of completed intentions relates to inter-phase settings; typically, increasing temporal delay between phases reduces activation levels and promotes intention representation deactivation. Increasing inter-phase task load may interfere with retrieval of completed PM intentions. Both approaches facilitate aftereffect deactivation. Conversely, reducing inter-phase delay and task load may more easily form PM aftereffects.

Regarding individual characteristics, cognitive aging associated with increasing age makes deactivation of completed PM intentions difficult, easily forming aftereffects. Executive control and output monitoring abilities are closely related to aftereffect deactivation; higher related abilities promote deactivation, while deficiencies more easily form aftereffects. Action-oriented individuals have advantages in initiating new intentions and inhibiting completed PM intentions, more likely promoting aftereffect deactivation. State-oriented individuals have difficulty deactivating completed intentions, more easily forming aftereffects.

3 Cognitive and Neural Mechanisms of Event-Based PM Aftereffect Formation and Deactivation

Most research on PM aftereffects has focused on influencing factors, with limited exploration of processing mechanisms. Many studies address mechanism questions through prospective interference effects, which refer to interference from PM intention execution on ongoing tasks (slower ongoing task reaction times) (Marsh et al., 2006; McDaniel & Einstein, 2000). In PM aftereffect research, reaction times during completion (including original PM cues and ongoing tasks) can be compared to baseline conditions (ongoing tasks only). If no differences exist, completed PM intentions do not consume cognitive resources, supporting automatic processing. If reaction times are slower in experimental than baseline conditions, completed PM intentions consume cognitive resources during completion, supporting controlled processing. Formation and deactivation of PM aftereffects may involve different mechanisms: formation relates more closely to automatic and monitoring processes, while deactivation depends more heavily on inhibitory processing.

3.1.1 Cognitive Processing Mechanisms of Event-Based PM Aftereffect Formation: Automatic and Strategic Monitoring Processing

Automatic processing theory posits that PM aftereffect formation does not consume cognitive resources and does not require allocating resources to monitor environments for original PM cues. During activation, encoded and executed PM intentions establish strong stimulus-response associations that remain highly activated. During completion, encountering original PM cues triggers spontaneous retrieval of completed PM intentions, causing aftereffects (Anderson & Einstein, 2017; Bugg et al., 2013; Cohen et al., 2020; Meier & Rey-Mermet, 2018; Scullin & Bugg, 2013; Scullin et al., 2011; Scullin et al., 2009). Automatic processing of completed PM intentions can be subdivided into reflexive-associative processing and discrepancy-plus-search processing (Kurtz et al., 2022; McDaniel et al., 2015; Scullin et al., 2013). Reflexive-associative processing suggests that after forming and storing PM intentions in long-term memory, encountering original PM cues reflexively reactivates stimulus-response associations between cues and intended actions (McDaniel et al., 2004; McDaniel et al., 2015), forming PM aftereffects. Discrepancy-plus-search processing suggests that performing specific responses to PM cues during ongoing tasks creates differential experiences that trigger automatic memory searches for the source of experienced discrepancies (Breneiser & Mcdaniel, 2006). By disrupting task processing fluency, this triggers subsequent automatic memory searches that retrieve completed PM intentions (Kurtz et al., 2022), forming aftereffects. Since both spontaneous retrieval processes may manifest as slowed ongoing task reaction times or commission errors during completion (Bugg & Streeper, 2019; Möschl et al., 2020), aftereffects reflected by these processes cannot be directly distinguished using discrete measures like reaction times or commission errors. Mouse-tracking technology can record continuous response data, tracking mouse movement direction and speed and providing information about cognitive processes occurring during response selection. Kurtz et al. (2022) combined this technique to examine whether PM aftereffects (based on commission errors, original PM cue and ongoing task reaction times) depend on reflexive-associative or discrepancy-plus-search processing. When comparing completion trials with original PM cues to ongoing task trials, decreased mouse movement speed would support discrepancy-plus-search processing, while increased movement curvature and angle would support reflexive-associative processing. They found that encountering original PM cues during completion increased mouse movement curvature and angle, validating reflexive-associative processing.

Controlled processing theory posits that PM aftereffect formation consumes cognitive resources. Based on resource allocation, it divides into strategic monitoring processing and inhibitory processing. Strategic monitoring suggests that completed PM intentions remain highly activated, and participants continue investing cognitive resources to actively search for and monitor them during completion, similar to preparatory attentional and memory processing. During completion, encountering original PM cues no longer requires specific key presses, only ongoing task responses. Because individuals continuously monitor original PM cues, they may strategically slow ongoing task responses after PM completion to increase opportunities for detecting original PM cues. While increasing detection opportunities may reduce commission errors, it increases interference with ongoing tasks during completion. PM aftereffect formation relates to top-down strategic monitoring or strategic slowing after intention completion. Therefore, more invested cognitive resources lead to stronger monitoring and greater likelihood of forming PM aftereffects (Meier & Rey-Mermet, 2012; Möschl et al., 2019; Strickland et al., 2018; Walser et al., 2012; Walser et al., 2017).

According to core assumptions of PM multiprocess theory, bottom-up and top-down processes involve all PM stages (encoding, storage, retrieval, execution, and deactivation) (Ellis, 1996; Kliegel et al., 2002; Matos & Albuquerque, 2021a). This theory suggests PM aftereffects involve two processes: spontaneous retrieval and inhibitory processing (Scullin & Bugg, 2013). Researchers have also proposed dynamic multiprocess theory, which suggests cognitive resource occupation during PM task completion is not simply present or absent but is selectively and dynamically allocated based on contextual features (Scullin et al., 2013; Shelton & Scullin, 2017). According to dynamic multiprocess theory, both bottom-up automatic and top-down strategic processes are involved when intentions are completed or no longer needed, with individuals dynamically adjusting cognitive resource investment based on task context (Bugg & Streeper, 2019; Matos & Albuquerque, 2021a). For example, when ongoing task load is low, sufficient resources exist to inhibit retrieval of completed PM intentions, but when load is high, insufficient resources lead to more automatic processing of completed intentions. Therefore, individuals dynamically adjust processing strategies across different ongoing task load blocks. Encountering original PM cues during completion (especially salient, focal cues) triggers spontaneous retrieval of prior intention content, an automatic process. Inhibitory processing suppresses retrieval or execution of completed intentions. Additionally, reflexive-associative and discrepancy-plus-search processes involved in spontaneous retrieval affect controlled processing involvement (Kurtz et al., 2022). Reflexive-associative processing only allows cognitive control to influence response levels to completed PM intentions by inhibiting execution triggered by conditioned reflexes (Bugg et al., 2016). If completed intentions are retrieved via reflexive-associative processing, cognitive control may only inhibit execution after retrieval (late inhibition). Discrepancy-plus-search processing allows cognitive control to function at the memory level, inhibiting memory searches for associations with experienced discrepancies when encountering original PM cues (Anderson & Einstein, 2017). If retrieval occurs via discrepancy-plus-search, cognitive control may have already inhibited or interrupted the memory search, preventing retrieval of completed PM intentions (early inhibition). Therefore, according to dual-process and dynamic multiprocess theories, individuals may dynamically adjust cognitive strategies during aftereffect formation. Completed PM intentions trigger automatic processing, and individuals may inhibit original PM responses; when cognitive control is impaired, inhibitory failure occurs, forming PM aftereffects.

In summary, during completion, both repeating completed PM intentions and interference from completed intentions on ongoing tasks form PM aftereffects. Encountering completed PM intentions and spontaneously retrieving them more easily produces commission errors (Anderson & Einstein, 2017; Scullin & Bugg, 2013; Scullin et al., 2011; Scullin et al., 2009). Sustained monitoring of completed PM intentions during completion prolongs reaction times to original PM cues and ongoing tasks, interfering with ongoing tasks (Meier & Rey-Mermet, 2012; Möschl et al., 2019; Walser et al., 2012; Walser et al., 2017). Dual-process and dynamic multiprocess theories support both spontaneous retrieval and inhibitory processing of completed intentions; when cognitive resources are insufficient, PM aftereffects form, but when resources are sufficient, aftereffect deactivation is promoted. Therefore, automatic and monitoring processes may more effectively explain PM aftereffect formation.

3.1.2 Neural Mechanisms of Event-Based PM Aftereffect Formation

Since PM aftereffect formation closely relates to automatic and monitoring processes, reviewing relevant neural pathways can clarify its neural mechanisms. Beck et al. (2014) used functional magnetic resonance imaging (fMRI) to dissociate brain activation related to automatic and monitoring processes in PM aftereffects. Encountering original PM cues during PM completion activated the insula, posterior cingulate cortex, ventral frontoparietal network, and medial temporal lobe, which relate to spontaneous retrieval of PM intentions (Beck et al., 2014; Cona et al., 2015), see Figure 1 [Figure 1: see original paper]. Spontaneous retrieval in reflexive-associative and discrepancy-plus-search processes activates similar but somewhat different brain regions. During completion, the insula selectively processes and amplifies relevant features of PM cues, then transmits this information to the posterior cingulate cortex (Cona & Rothen, 2019). In discrepancy-plus-search spontaneous retrieval, information transmitted to the posterior cingulate is further sent to the ventrolateral frontal cortex, which supports shifting attentional resources from external cues to internal memory to search for corresponding stored traces. After PM completion, repeated original PM cues still trigger retrieval of corresponding intention representations from long-term memory, involving retrospective or episodic memory retrieval processes that activate medial temporal lobe regions. The medial temporal lobe establishes automatic associations between cues and intention activities and maintains them in an activated state; encountering original PM cues spontaneously retrieves relevant intention content, forming PM aftereffects (Beck et al., 2014; Scullin et al., 2020; 黄欢等, 2018). Similarly, reflexive-associative spontaneous retrieval also involves the insula, posterior cingulate cortex, and medial temporal lobe. Unlike discrepancy-plus-search processing, information transmitted to the posterior cingulate is first sent to the rostrolateral prefrontal cortex, which maintains completed PM intentions in an activated state in long-term memory, then activates and reflexively retrieves completed PM intentions through the ventrolateral parietal cortex, forming PM aftereffects (Beck et al., 2014; Cabeza & Moscovitch, 2013).

In strategic monitoring, information about repeatedly appearing original PM cues is first amplified by the insula, then signals of completed PM intention occurrence are transmitted to the anterior cingulate cortex. During completion, original PM cues and ongoing task stimuli may generate competing conflict signals, activating the anterior cingulate. The insula and anterior cingulate together constitute the "salience network," which detects internal and external information related to PM intentions. The anterior cingulate typically co-activates with dorsolateral prefrontal cortex and posterior parietal cortex, forming a "cognitive control network structure" that monitors completed PM intentions (Beck et al., 2014; Cona et al., 2015; Friedman & Robbins, 2022; 黄欢等, 2018). The anterior cingulate transmits conflict signals between original PM cues and ongoing tasks to the dorsal frontoparietal network. The dorsal frontoparietal network, comprising dorsolateral prefrontal cortex, precuneus, and posterior parietal cortex, relates to strategic monitoring processing, see Figure 2 [Figure 2: see original paper]. Based on these signals, the dorsal frontoparietal network top-down allocates attention and modulates processing of relevant stimulus features in sensory cortices according to ongoing task and original PM cue response requirements, maintains activation of completed PM intentions, and monitors for original PM cue appearance. Greater cognitive resource investment more easily forms PM aftereffects (Cona & Rothen, 2019; Cona et al., 2015).

3.2.1 Cognitive Processing Mechanisms of Event-Based PM Aftereffect Deactivation: Inhibitory Processing

Unlike PM aftereffect formation, deactivation relates more closely to inhibitory processing. Inhibitory processing suggests that activation levels of PM intention representations are actively reduced after intention completion. Activation levels of PM-related memory content may decrease below baseline, involving active inhibition of completed PM intention-related memory content. Another view suggests inhibitory processing reduces activation levels to near but not below baseline, not involving active inhibition but rather processes involved in deactivating completed PM intentions. Moreover, inhibiting completed PM intentions helps establish new intention representations (El Haj et al., 2018; Matos & Albuquerque, 2021a; Möschl et al., 2020). Strong PM intentions formed during activation require cognitive resource investment to inhibit them during completion when original PM tasks are no longer required, ensuring ongoing task execution. However, inhibitory processing may involve two different modes: first identifying original PM cues then inhibiting completed PM intentions, or direct inhibition (without cue identification). The former means during completion, original PM cues are first identified, then cognitive resources are invested to inhibit completed PM intentions. The latter means during completion, individuals may not identify original PM cues but treat the entire completion block as ongoing task trials, directly inhibiting identification of original PM cues and execution of completed PM intentions.

Stop-tag theory suggests that during activation, deep episodic traces and rich intention completion representations are formed for PM intentions, and completion phase instructions bind stop-tags to cognitive representations of no-longer-relevant cue-response associations, more easily forming "No-Go" memories (Bugg & Scullin, 2013; Bugg et al., 2016). According to memory reconsolidation theory, when memories are reactivated, they temporarily become unstable. In this unstable state, memories can be terminated (Nader & Hardt, 2009). Encountering original PM cues during completion reactivates goal-action associations, making them temporarily unstable and ready for memory termination. Therefore, original PM cues no longer trigger memory for original PM intentions during completion, promoting aftereffect deactivation.

According to dynamic multiprocess theory, during aftereffect deactivation, individuals also spontaneously retrieve completed PM intentions, but those with higher cognitive control can more successfully inhibit and deactivate them (Bugg & Scullin, 2013; Bugg et al., 2016; Bugg & Streeper, 2019; Kurtz et al., 2022; Matos et al., 2020; Schaper & Grundgeiger, 2019; Scullin & Bugg, 2013). When individuals realize PM intentions are completed, they may inhibit intention activation and original PM responses (Bugg et al., 2016) and may bind stop-tags to PM cue-response associations to encode new intentions for not performing previous actions when encountering original PM cues again (Bugg & Scullin, 2013). Both formation and deactivation involve dual-process mechanisms: the former results from insufficient inhibition, forming aftereffects, while the latter involves higher inhibition levels, deactivating completed intentions. Combining automatic, controlled, and dual-process theories, an extraction-inhibition processing model may also exist, which essentially requires first identifying original PM cues then inhibiting completed PM intentions (Matos & Albuquerque, 2021a; Möschl et al., 2020), partially explaining aftereffect deactivation. Extraction-inhibition processing can be divided into automatic extraction-inhibition and monitoring extraction-inhibition. Automatic extraction-inhibition aligns with dual-process theory, while monitoring extraction-inhibition involves sustained monitoring of completed PM intentions, extracting then inhibiting them. Because individuals continuously invest cognitive resources to monitor completed PM intentions, encountering original PM cues during completion first leads to identification, then extraction, consuming cognitive resources. After completed PM intentions are extracted, inhibitory processing is required for deactivation. Therefore, high-level inhibitory processing more easily promotes deactivation, while low-level inhibitory processing makes deactivation difficult. Currently, only a few studies suggest possible extraction-inhibition processing models, but none have systematically distinguished automatic from monitoring extraction-inhibition; future research should use unified experimental paradigms to differentiate them.

In PM aftereffect research, participants are typically told during completion to treat original PM cues as ongoing task trials without performing original PM responses, involving inhibition of completed PM intention retrieval and execution (Möschl et al., 2020; Pink & Dodson, 2013; Scullin & Bugg, 2013; 郭云飞等, 2019; 辛聪等, 2020). Stop-tag theory, dual-process, and dynamic multiprocess theories all involve inhibitory processing concepts; to deactivate completed PM intentions, cognitive resources must be invested to inhibit them or form readiness to not execute during completion. Therefore, inhibitory processing may more effectively explain PM aftereffect deactivation.

3.2.2 Neural Mechanisms of Event-Based PM Aftereffect Deactivation

PM aftereffect deactivation is closely related to inhibitory processing, which involves not only the insula, anterior cingulate, dorsolateral prefrontal cortex, precuneus, and posterior parietal cortex, but also the rostral prefrontal cortex, lateral orbitofrontal cortex, and supplementary motor area (Cona & Rothen, 2019; Cona et al., 2015; Scullin et al., 2020). During completion, information related to original PM cues is amplified by the insula and transmitted to the anterior cingulate. Since PM responses to completed intentions are no longer needed, encountering original PM cues generates response conflict signals, and individuals must inhibit responses to completed PM intentions, activating the anterior cingulate and rostral prefrontal cortex. The lateral orbitofrontal cortex relates to establishing new stimulus-response associations and inhibiting old dominant responses; together with dorsolateral prefrontal cortex, precuneus, and posterior parietal cortex, it forms a frontoparietal network that inhibits retrieval of completed PM intentions (Cona & Rothen, 2019; Scullin et al., 2020). Successful inhibition of completed PM intentions also relates to the supplementary motor area, which is involved in selecting appropriate behavioral responses and inhibiting inappropriate task responses. The supplementary motor area, combined with multiple somatosensory regions, translates completed PM intentions from abstract awareness to concrete action—that is, inhibitory processing of completed PM intentions (Cona et al., 2015; Emanuel et al., 2021). When cognitive resources are sufficient, inhibition of completed PM intentions is promoted, leading to aftereffect deactivation (see Figure 2).

Recently, Scullin et al. (2020) found moderate correlations between older adults' medial temporal lobe and lateral orbitofrontal cortex volumes and commission errors: larger medial temporal lobe and smaller lateral orbitofrontal cortex volumes more easily produce PM aftereffects. They argued that PM aftereffects involve dual-process mechanisms: during automatic processing, the medial temporal lobe participates in associations between cues and intention activities, maintaining them in an activated state in long-term memory. Therefore, larger medial temporal lobe volume more easily promotes spontaneous retrieval of completed PM intentions. Additionally, the lateral orbitofrontal cortex relates to inhibiting old habitual responses after learning new stimulus-response associations, evaluating the appropriateness of previous stimulus-response occurrences in current contexts, and relates to decision-making and difficulty in cognitive control responses (Izquierdo et al., 2017). During completion, individuals must judge whether to continue PM responses to original PM cues, involving cognitive control processes consistent with controlled processing perspectives. Although no study has systematically reviewed the neural mechanisms of dual-process theory in PM aftereffects, speculation is possible based on neural pathways involved in automatic and inhibitory processing (see Figure 3 [Figure 3: see original paper]). During completion, information related to original PM cues is amplified by the insula and transmitted to the cingulate cortex, potentially activating neural pathways related to both automatic and inhibitory processing. Deactivation of completed PM intentions depends on inhibitory processing; when cognitive resources are sufficient, aftereffect deactivation is promoted, but when resources and inhibitory control are insufficient, inhibitory failure occurs, causing PM aftereffects. Additionally, the neural mechanisms of the extraction-inhibition processing model can be speculated from brain regions activated in automatic, monitoring, and inhibitory processing. Future research needs to increase investigation of PM aftereffect neural mechanisms and systematically review brain regions involved in aftereffect deactivation.

4 Summary and Outlook

Completed PM intentions may not fully deactivate, causing commission errors or interfering with ongoing task performance—that is, producing PM aftereffects. Based on PM multiprocess theory, factors influencing PM aftereffects can be categorized as PM task characteristics, ongoing task characteristics, task context, and individual traits. Current cognitive mechanisms of PM aftereffect formation and deactivation mainly involve automatic processing, controlled processing (monitoring, inhibition), extraction-inhibition processing, stop-tag processing, dual-process, and dynamic multiprocess frameworks. Among these, automatic processing subdivides into reflexive-associative and discrepancy-plus-search processing, while controlled processing divides into monitoring and inhibitory processing. Extraction-inhibition processing includes automatic extraction-inhibition and monitoring extraction-inhibition. Neuroimaging evidence suggests PM aftereffects may involve neural pathways for automatic, controlled, and dual-process mechanisms. However, research on PM aftereffects has several limitations requiring further investigation:

4.1 Deepen Investigation of Event-Based PM Aftereffect Processing Mechanisms

Several important questions about PM aftereffect processing mechanisms remain unclear. First, in automatic processing, the extent and conditions under which reflexive-associative and discrepancy-plus-search spontaneous retrieval participate in processing completed PM intentions are not clear. Most studies only infer automatic processing from results without directly investigating relationships between these spontaneous retrieval types and PM aftereffects. Similarly, it remains unclear when cognitive control participates in deactivating completed PM intentions. Moreover, does cognitive control inhibit retrieval of completed PM intention content, or merely inhibit execution of completed intentions, or both? Second, previous mechanism investigations only analyzed data from participants showing PM aftereffects (commission errors or interference), assuming those without aftereffects successfully inhibited completed PM intentions without spontaneous retrieval. However, if participants without commission errors show slower responses to original PM cues than baseline, they may still spontaneously retrieve completed PM intentions despite inhibiting repetition (Matos & Albuquerque, 2021a). Finally, only two studies have directly investigated PM aftereffect neural mechanisms, both using small samples of middle-aged and older adults (Beck et al., 2014; Scullin et al., 2020), limiting generalizability. Therefore, future research should further investigate PM aftereffect processing mechanisms, combining neuroimaging to comprehensively explain differences between reflexive-associative and discrepancy-plus-search processing in spontaneous retrieval, determine which stage after intention completion involves cognitive control, and clarify response indicators involving inhibitory and monitoring processing. Neuroimaging can explore which intention representation deactivation relates to PM aftereffect generation. Additionally, future research should use larger samples and conduct functional neuroimaging studies of PM aftereffects in healthy young adults, middle-aged and older adults, and clinical populations, comprehensively analyzing data from participants with and without aftereffects to further clarify mechanism issues.

4.2 Increase Investigation of PM Aftereffects Across Different Types and Naturalistic Contexts

Current PM aftereffect research primarily uses paradigms developed for event-based PM, which may not fully capture PM aftereffects. Different PM types have different cognitive resource demands. In event-based PM tasks, target events may automatically activate intention content retrieval. In time-based PM, intention retrieval requires self-related initiation, demanding higher executive control resources as individuals must actively monitor target contexts and attend to time information changes to ensure successful execution (Einstein & McDaniel, 1990). Event-based PM paradigms include clear external cues, measuring aftereffects by observing responses to original PM cues during completion, whereas time-based PM lacks obvious external cues, making it difficult to use the same measures and requiring alternative indicators. For example, time monitoring frequency and repeated PM key presses during completion may be time-based PM aftereffect indicators. Currently, no research has examined time-based PM aftereffects; future studies should design paradigms measuring time-based PM aftereffects based on existing paradigms and time-based PM features.

Most PM aftereffect research occurs in laboratory contexts, which differ from real-life situations. Laboratory contexts typically have shorter PM intention maintenance phases, with participants usually encountering the first PM cue after only a few ongoing task trials. Shorter intention maintenance during completion may prevent sufficient time for completed PM intentions to deactivate, potentially overestimating aftereffects. Moreover, real-world PM typically requires more complex action plans. Additionally, laboratory assessments rely primarily on objective indicators like commission errors or reaction times. Schaper and Grundgeiger (2019) suggest participants may not realize during completion that executing completed PM intentions is erroneous. Do individuals have thoughts about activating or inhibiting PM intention-related content when encountering original PM cues during completion? Future research should increase investigation of PM aftereffects in naturalistic contexts, using more complex action plan paradigms to approximate real situations. Furthermore, researchers could collect subjective evaluation information during PM completion, asking participants to report thoughts about completed PM intentions, combining subjective and objective measures to increase understanding of PM aftereffects.

4.3 Focus on Exploring Strategies to Reduce PM Aftereffects

Research shows both young and older adults may experience PM aftereffects, particularly pronounced in older adults (Bugg et al., 2016; Scullin et al., 2012; Scullin et al., 2009). Current PM aftereffect research focuses primarily on healthy young and older adults, with few studies examining clinical populations. El Haj et al. (2018) found Alzheimer's patients showed more commission errors than healthy older adults, having difficulty both retrieving PM-related information and inhibiting completed PM intentions. Therefore, future research should expand investigation of PM aftereffects in clinical populations, focusing on strategies to reduce aftereffects, which can effectively improve daily life quality and have important clinical significance.

Bugg et al. (2016) found that forgetting practice strategies effectively reduce PM aftereffects. Forgetting practice involves participants performing practice tasks before stimulus presentation—when encountering previous targets, they only perform current tasks without PM responses. This strategy essentially reduces aftereffects by inhibiting repetition of completed intentions, aiming to help individuals forget previous intentions and form "No-Go" memories through practice training (Bugg et al., 2016). Research shows external reminders can also improve PM; for example, daily life tools like sticky notes, memos, or alarms can prompt task execution (Faytell et al., 2018; Jones et al., 2021). Anderson and Einstein (2017) suggest that creating daily medication checklists as information cues can effectively reduce PM aftereffects in clinical patients. External cue prompts are highly manipulable in daily life, making them commonly used strategies. Currently, only a few studies have examined strategies to reduce PM aftereffects, despite their significant negative impact on daily life. Future research should increase investigation of strategies to reduce PM aftereffects to improve people's daily life quality.

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Note: Figure translations are in progress. See original paper for figures.