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the recognition memory parameter was lower. Previous findings suggest that increased similarity between targets and distractors can reduce recognition performance.²⁷ The manipulation of distinctiveness also affected the P parameter of the model in an opposite manner than it affected M . If targets and nontargets came from the same categories, the likelihood of engaging in preparatory attentional processes (P) increased, whereas the M parameter decreased (see above). It is plausible that higher semantic similarity increases the need for preparatory attention because items are harder to discriminate and the detection of targets requires more resources; furthermore, nontargets that are similar to target items can serve as cues and remind participants to engage in preparatory attention.²⁸ Finally, manipulations of ongoing task difficulty affected exclusively participants' detection accuracy in the ongoing task (C parameters): if the number of color rectangles shown during an ongoing task trial was increased (thereby making detection harder), this reduced accuracy as measured by the C parameters.²⁹

Outlook

As summarized in the previous paragraph, the present model successfully passed a series of validity tests in which experimental manipulations influenced the parameters P , M , and C selectively and in predictable ways. Given that *goodness of fit* indices were acceptable in most cases, this indicates that the model can be fruitfully applied in the domain of event-based PM. For instance, researchers have shown that interindividual differences in working memory span can account for variability in PM performance.³⁰ Application of the mathematical model provided evidence for a positive relationship between available capacity in working memory, the likelihood of engaging in preparatory attention (P), and successful PM.³¹ Furthermore, in a cognitive aging study, the model was used to investigate differences of healthy younger and older adults' PM performance. The modeling results revealed a decline in the resource-demanding prospective component (P) in the group of older adults.³² Thus, the model provides information that cannot be obtained solely through the application of traditional data analytic approaches.

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²⁷ Cf. Bayen *et al.* (1996), Hunt (2003).

²⁸ Cf. Taylor *et al.* (2004).

²⁹ Cf. Horn (2007).

³⁰ Cf. Smith (2003).

³¹ Cf. Smith and Bayen (2005).

³² Cf. Smith and Bayen (2006).

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high-threshold models of old-new recognition memory.²⁰ The remaining free parameters P , M , C_1 , and C_2 then can be determined in a globally identifiable model.

Validation Experiments

A selected model must be tested before it can be applied to research questions of interest. There are two essential aspects of testing a model-based theory, namely fit and validity. In *goodness of fit* tests, discrepancies between model predictions and empirical data are assessed statistically. A poor fit will result whenever the properties of empirical data violate the restrictions imposed by a model. The statistic G^2 can be used to test fit in multinomial modeling.²¹ Models that fail to pass such tests repeatedly with different data sets (i.e., more than $n \cdot \alpha$ times) must be rejected. Evaluating the fit of a model is a necessary first step, but it cannot replace more conceptual assessments provided by *experimental validation*. The objective of experimental validation is to test whether particular parameters reflect corresponding cognitive processes as postulated in the model. For each parameter, at least one experimental manipulation is chosen that can be expected to have well-established, theoretically predictable effects on the basis of prior research; a discriminant validity test is passed if a parameter changes *selectively*, whereas the other parameters remain unaffected. The validity of the present MPT model of event-based PM was tested in a series of experiments, which are briefly reviewed here; predictable and separable effects on the free parameters P , M , C_1 , and C_2 could be demonstrated. The first two parameters are of main interest because they are assumed to measure prospective and retrospective memory processes independently.²²

First, instructions emphasizing either the importance of the PM task or the importance of the ongoing task influenced exclusively the P parameter of the model.²³ If participants were initially instructed that the PM task was more important than the ongoing task, the probability of engaging in preparatory attentional processes (P) increased, leading to higher PM performance. This effect was expected from several previous findings that reported a higher likelihood to realize intentions that are considered important.²⁴ Second, manipulations of available encoding time for PM target items influenced exclusively the recognition memory parameter M of the model.²⁵ When participants were initially given 20 seconds to study each PM target item, subsequent discrimination between targets and nontargets (M) during the experiment was higher than with only five seconds study time per item. Better recognition memory following longer encoding time is a well-established result in the memory literature. Third, manipulating the distinctiveness of PM target items affected the M parameter of the model.²⁶ When the target items came from different semantic categories than the nontarget items in the ongoing task, recognition memory increased because the targets appeared more salient than in a same-category condition. On the other side, if targets and nontargets came from the same categories, the estimate for

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²⁰ Cf. Snodgrass and Corwin (1988).

²¹ Cf. Hu and Batchelder (1994).

²² Cf. Smith and Bayen (2004).

²³ Cf. Smith and Bayen (2004, Experiments 1 and 2).

²⁴ Cf. Kliegel *et al.* (2004).

²⁵ Cf. Smith and Bayen (2004, Experiments 3 and 4).

²⁶ Cf. Smith and Bayen (2004, Experiment 2).

when participants do not engage in preparatory attentional processes ($1 - P$), the target word cannot be noticed and there is no intention to give a “PM” response. Still, the word is detected as a color match, resulting in a “Yes” response. The bottom half of the tree represents the case in which the color of the word is not detected as a match ($1 - C_1$) and the color-matching response is made under uncertainty. Participants may engage in preparatory attentional processes (P) and recognize the item as a target word (M_1), resulting in a “PM” response. If the item is not recognized as target ($1 - M_1$), participants guess (g) or do not guess ($1 - g$) that the item is a target. In the latter case, there is now an additional possibility to guess (c) or not to guess ($1 - c$) that the color of the word matches. If there is no engagement in preparatory attentional processes ($1 - P$), participants now guess (c) or do not guess ($1 - c$) that the color of the word is a match, resulting in a “Yes” or “No” response, respectively. The second tree represents latent processes when a PM target word is presented but its color does not match (target, nonmatch trial). It is the same as the first tree, except for parameter C_2 , the probability to detect that the color of a word does *not* match one of the colors in the preceding set of rectangles. The third and fourth trees represent latent processes for nontarget match trials and nontarget nonmatch trials, respectively. The parameter M_2 in these last two trees represents the probability to recognize that a word is *not* a PM target.

PAM theory suggests that successful PM always relies on preparatory attentional processes. Furthermore, it is suggested that preparatory attention is a prerequisite for recognition memory processes to come into play. As Figure 1 shows, both aspects are reflected in the model. Firstly, “PM” responses never follow in the absence of the P parameter. Secondly, the parameters M_1 , M_2 , and g occur only in those branches that also include P . That is, participants do not discriminate targets from nontargets or guess that words are targets unless they are in a preparatory state to do so. For this reason, preparatory attentional processes (P) must be engaged independently of trial type and occur in all four trees of the model, on target trials as well as on nontarget trials. Because the number of free parameters exceeds the number of independent model equations, the seven-parameter model as presented in Figure 1 is not globally identifiable.¹⁶ That is, parameter values cannot be uniquely determined from the observed categorical frequencies and it can be shown that the model must be restricted to a four-parameter version for identifiability.¹⁷ Theoretically motivated restrictions can be made by either assuming equality between model parameters or by setting them to specified values. In the present model, guessing parameters c and g were set to fixed values. Individuals sometimes calibrate their response tendencies to the perceived ratio of presented items during an experiment, known as probability matching.¹⁸ Following this rationale, c is set to the match-to-nonmatch ratio of the experiment and g is set to the target-to-nontarget ratio (i.e., $c = .50$; and $g = .10$ in the present case). Similar approaches have been taken in other MPT models.¹⁹ A further constraint is imposed on the M parameters by assuming that PM target words and nontarget words are equally well recognized (i.e., $M_1 = M_2$). This standard assumption has been successfully made in two-

¹⁶ Cf. Erdfelder (2000).

¹⁷ Cf. Smith and Bayen (2004, Appendix A).

¹⁸ Cf. Spaniol and Bayen (2002).

¹⁹ Cf. Klauer and Wegener (1998).

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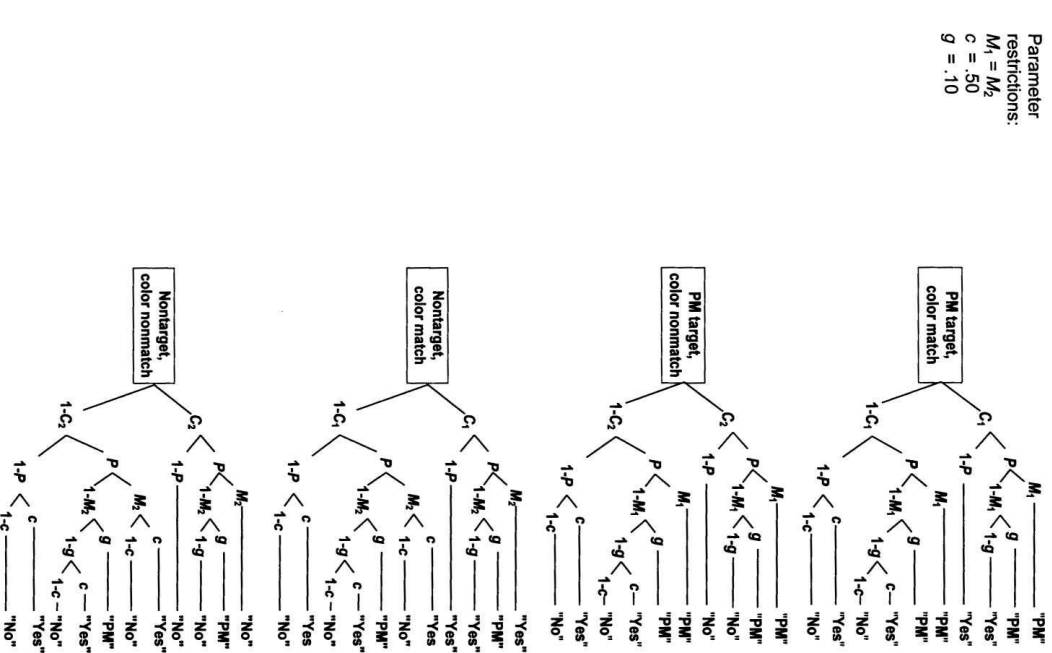


Figure 1: The multinomial processing tree model of event-based PM for three responses. PM = prospective memory; C_1 = probability of detecting a color match; C_2 = probability of detecting that a color does not match; P = preparatory attentional processes; M_1 = probability of detecting that a word is a PM target; M_2 = probability of detecting that a word is not a PM target; g = probability of guessing that a word is a target; c = probability of guessing that a color matches. Note. From "A multinomial model of event-based prospective memory" by R. E. Smith and U. J. Bayen, 2004, *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 30, p. 758. © 2004 by the American Psychological Association.

between hypothetical constructs and their corresponding empirical measures. Importantly, mathematical modeling is not arbitrary but theoretically motivated and its assumptions can be tested and validated. Multinomial processing tree (MPT) models assume that experimental observations fall into a set of mutually exclusive and exhaustive categories $C_j, j = 1, \dots, J$ with probability p_j and $\sum_{j=1}^J p_j = 1$. The observed response frequencies F_j in category C_j are regarded as realizations of underlying cognitive states. It is assumed that cognition involves a set of such discrete, internal states. Given independent and identically distributed observations, the data can be formalized with a multinomial distribution:

$$P(F_1, \dots, F_j; p_1 \dots p_j) = N! \prod_{j=1}^J \frac{p_j^{F_j}}{F_j!}.$$

The probability of an internal state is described with independent parameters $\theta_1, \dots, \theta_s$ that are determined from the data using maximum likelihood estimation. MPT models are flexible tools that have been successfully applied in many fields of psychology.¹⁴

The present MPT model was introduced to disentangle processes of interest in event-based PM.¹⁵ It can be applied to any laboratory experiment in which PM target events are embedded in ongoing tasks with two response alternatives. The two-choice color-matching task mentioned above meets this criterion. When using this paradigm, four resulting trial types can occur during an experiment (shown on the left side of Figure 1): target words whose color matches one of the previously shown rectangles (target, match trial), target words whose color does not match one of the previously shown rectangles (target, nonmatch trial), nontarget words whose color matches (nontarget, match trial), and nontarget words whose color does not match (nontarget, nonmatch trial). The model assumes that responses to these trials are the combined result of processes that can be represented by seven independent parameters. In accord with PAM theory, separate estimates for preparatory attentional processes (P) and for retrospective recognition memory (M_1 and M_2) are provided. Furthermore, processing of ongoing task stimuli (C_1 and C_2) and two separate guessing processes (c and g) are included. Figure 1 illustrates how these processes are thought to interact in the model. As can be seen, the model consists of four different processing trees that result from the trial types on the left side. For each trial type, mediating latent processes lead to an observable response on the right side; every branch is a product of parameters. Three possible response categories are taken into account: responding with “Yes”, with “No”, or giving a “PM” response. The response categories appear repeatedly because different processes can lead to the same observable response. Thus, the probability for a particular response category is obtained by summing all branches of a processing tree leading to that category. The top tree in Figure 1 represents the case in which a PM target word is shown and its color matches with one of the preceding colored rectangles (target, match trial). Regarding the upper half of this tree, C_1 represents the probability to correctly detect the color of the word as a match. With probability P , participants engage in preparatory attentional processes. With probability M_1 , the target word is recognized as such, resulting in a “PM” response. When a target word is not recognized ($1 - M_1$), participants can either guess (g) or not guess ($1 - g$) that the item is a target. However,

¹⁴ Cf. Batchelder and Riefer (1999).

¹⁵ Cf. Smith and Bayen (2004).

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target events in order to recognize the target events as an opportunity to carry out the intention; these processes are not triggered by the targets and are thought to be non-automatic. That is, the PAM theory stands in contrast to views proposing that intentions are retrieved through entirely automatic operations that are involuntary, that do not draw on limited mental capacity, and that do not interfere with other ongoing activities. PAM theory assumes that preparatory attentional processes can range from explicit strategic monitoring of the environment for target events to more subtle processes outside the focus of attention, on the periphery of awareness. Accordingly, introspective reports about the presence or absence of a deliberate monitoring strategy are not reliable indicators for preparatory attention.⁹ While the PAM theory proposes that non-automatic preparatory attentional processes are required, automatic processes are also involved in performance. The important distinction is that the automatic processes will never be sufficient on their own for retrieval of the intention at the appropriate opportunity. On the other hand, preparatory attentional processes are not sufficient either for successful PM performance: additional retrospective memory processes must follow to recognize the target events and to recollect the content of a previously formed intention. Similar to old-new recognition tasks, individuals must discriminate target events from nontarget events and, similar to recall tasks, they must recollect the intention. According to PAM theory, retrospective memory does not come into play unless preparatory attentional processes are previously engaged.

A compromise position is taken in the multiprocess framework.¹⁰ It is argued that in some PM tasks automatic processes alone can lead to the retrieval of intentions. Dependent on various characteristics of the given PM task, the ongoing task, and the individual, a particular retrieval mechanism is thought to predominate. According to this theory, there is a tendency for the individual to rely on automatic, spontaneous retrieval to save capacity for other tasks at hand. For instance, if the PM task involves a single target event and if “focal” processing is involved, then retrieval is predicted to be automatic. Processing is considered to be “focal” if information extracted during an ongoing activity emphasizes the previously encoded defining features of target events (i.e., when the intention was formed).¹¹ While there is evidence that PM tasks involving a single target and a focal task do involve non-automatic processes,¹² the controversy continues regarding whether automatic activation can be sufficient in some situations to notice target events or whether resources for preparatory attentional processes are always required.

The Multinomial Model

As outlined above, theories of cognitive psychology rely on assumptions about hypothetical latent processes, for instance those involved in the prospective or retrospective components of a PM task. A fundamental objective in cognitive psychology is to disentangle the processes that underlie observable behavior. The main advantage of a *model-based approach*¹³ to cognitive psychology is a clear mathematical specification of the relationship

⁹ Cf. Smith (2008).

¹⁰ Cf. McDaniel and Einstein (2000).

¹¹ Cf. McDaniel and Einstein (2007).

¹² Cf. Smith *et al.* (2007).

¹³ Cf. Brainerd (1985).

numerous memory experiments: it includes remembering what you wanted to do and recognizing the relevant target events. The *prospective component* is the part that leads to noticing *that* there is something which must be done. It is this latter requirement – not only to remember but “remember to remember” – that can be regarded as crucial feature of PM. Accordingly, PM research has focused on the processes underlying the prospective component and on approaches to disentangle them from retrospective memory processes.

Experimental Paradigm

To study PM in the laboratory, a paradigm is widely used that can be applied to both event-based and time-based tasks.⁵ Simulating real world situations, an essential characteristic of this procedure is to busily engage individuals in an ongoing activity while they additionally must remember to perform a PM task at relevant moments. Such a dual-task design seems appropriate because PM tasks in our daily lives rarely occur in isolation. For instance, on the way home from work we may be driving a car, watching the traffic, and listening to the radio but then have to remember to stop at the bakery at the right moment. A second important characteristic of this paradigm is to induce forgetting to make the demands of the prospective component sufficiently challenging in the laboratory. Besides embedding the PM task into an ongoing task, participants are distracted for a short interval after the initial PM instructions. Taken together, these features provide a basis for a systematic exploration of PM. As a concrete example of this paradigm, let us briefly describe the color-matching task that we have used in previous studies as an ongoing activity.⁶ In this visual short-term memory task, rectangles are shown sequentially for a short period of time in the middle of a screen, each in a different color. Then a word is presented in a specific color and participants have to decide whether it matches one of the previously shown colors by making binary responses, “Yes” or “No”. Importantly, before starting with this ongoing activity, a few words are presented as target events. Participants are instructed to remember these words and make an extra “PM” response whenever one of them occurs during the color-matching task (the PM intention). Finally, to prevent ceiling effects in PM performance and to reduce the possibility that the PM task becomes a vigilance task, participants work on a different distractor activity for a few minutes after the initial instructions.

Theoretical Accounts

Much theoretical work has focused on the question of how our cognitive system enables us to retrieve previous intentions at the appropriate point for performance. Several theories postulate that mental resources can be necessary for event-based PM. Preparatory attentional and memory processes theory (PAM)⁷ takes the strong stance that resources from a limited pool of capacity⁸ must *always* be allocated for successful PM. It is assumed that individuals must engage in preparatory attentional processes prior to the occurrence of

⁵ Cf. Einstein and McDaniel (1990).

⁶ Cf. Horn (2007), Smith and Bayen (2004), Smith and Bayen (2006).

⁷ Cf. Smith (2003), Smith and Bayen (2004).

⁸ Cf. Kahneman (1973).

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A Multinomial Model of Event-Based Prospective Memory

Introduction

In 1994, a passenger aircraft departing from La Guardia airport in New York ran off the runway because the crew did not carry out a simple action that had been trained to do many times before. A more detailed investigation attributed the main cause of this accident to a failure to remember a prior intention.¹ Although not always connected with serious consequences, comparable everyday problems are well-known: forgetting to buy bread on the way home from work, to attach a file to an email, or to take one's daily medication are all examples of this sort. While errors do occur, it is equally remarkable that individuals often perform their goals successfully hours or days after forming the intention, during which time the intentions have left conscious awareness. Such memory phenomena have been a matter of interest in philosophy and psychology for a long time.² However, only in the last decades have psychologists studied the remembering of intentions in more depth with experimental techniques using the term *Prospective Memory* (PM).³ In the present text, we illustrate some theoretical background and describe the paradigm used in PM research. Furthermore, we introduce a model-based approach as an important part of our work and review the empirical findings with regard to model testing.

What is Event-Based Prospective Memory?

It should be clear from the above examples that PM refers to memory for intentions to be retrieved at a specific point in the *future*; such tasks can be classified according to different retrieval occasions.⁴ In *event-based* PM tasks, the intention is associated with a specific (target) event and its occurrence defines the appropriate time for execution. For example, the intention to buy bread on the way home from work can be executed as soon as we pass a bakery after work and the occurrence of any bakery would be the appropriate target event. An important property of event-based tasks is that targets are physically present whenever an intention becomes relevant. In *time-based* PM tasks, an intention is associated solely with the variable of time (a specific clock time or an amount of time elapsed). Examples are the intention to attend a meeting at 1:30 p.m. or to switch off the oven after 25 minutes. Another theoretical distinction assumes that any PM task can be broken into two components. The *retrospective component* is the part that has been traditionally studied in

1 Cf. Dismukes and Nowinski (2007).

2 Cf. Lewin (1926).

3 Cf. Meacham and Leitman (1975).

4 Cf. Einstein and McDaniel (1990).