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Inhalt

Vorwort des Rektors Alfons Labisch 11

Grußwort des Amtsnachfolgers H. Michael Piper 17

Gedenken 19

Hochschulrat

Anne-José Paulsen
Der Hochschulrat der Heinrich-Heine-Universität Düsseldorf 23

Rektorat 29

Alfons Labisch
Zur Lage und zu den Perspektiven der deutschen Universität in unserer Zeit 31

Matthias Hofer, Natalie Böddicker und Hildegard Hammer
Lehren – entweder man kann es, oder man kann es lernen! Hochschuldidaktik an der Heinrich-Heine-Universität Düsseldorf 43

Hildegard Hammer, Doris Hildesheim, Victoria Meinschäfer und Jutta Schneider
Die Campus-Messe der Heinrich-Heine-Universität 61

Medizinische Fakultät

Dekanat 79

Neu berufene Professorinnen und Professoren 81

Bernd Nürnberg (Dekan)
Düsseldorfer Hochschulmedizin 2008: Die Zukunft hat längst begonnen 93

Inge Bauer, Leonie Halverscheid und Benedikt Pannen
Hepatoprotektive Wirkungen des Hämoxygenase-Stoffwechsels: Der Einfluss von Anästhetika 99

Arndt Borkhardt
Biologische Grundlagen der Immunrekonstitution nach allogener Stammzelltransplantation bei Kindern und Jugendlichen 117

Lars Christian Rump und Oliver Vonend
Pathomechanismen der arteriellen Hypertonie 127

Jörg Schipper
Gründung und Aufbau des „Hörzentrums Düsseldorf“ 141

ATTILA STEPHAN ANTAL, GABRIELA KUKOVA und BERNHARD HOMEY
Juckreiz: Vom Symptom zum Mechanismus 147

WOLFGANG WÖLWER und WOLFGANG GAEBEL
Kompetenznetz Schizophrenie: Konzept, Ergebnisse, Perspektiven 153

STEPHAN LUDWIG ROTH und WILFRIED BUDACH
Überlebensvorteil durch präoperative Radiochemotherapie beim lokal fortgeschrittenen, nicht-inflammatorischen Brustkrebs 171

GEORG WINTERER
Nikotin: Molekulare und physiologische Mechanismen im Zentralen Nervensystem – Ein neues nationales Schwerpunktprogramm der Deutschen Forschungsgemeinschaft 191

Mathematisch-Naturwissenschaftliche Fakultät

Dekanat 201

Neu berufene Professorinnen und Professoren 203

ULRICH RÜTHER (Dekan)
Die Mathematisch-Naturwissenschaftliche Fakultät im Jahr 2008 209

MARTIN MÖHLE
Nachkommen und Vorfahren im Blickpunkt der Mathematischen Populationsgenetik 213

JÜRGEN KLÜNERS
Faktorisierung von Polynomen – Ein wichtiges Problem der Computeralgebra 225

MARTIN LERCHER
Wie Bakterien an neue Gene kommen und was sie damit machen 237

MATTHIAS U. KASSACK, ALEXANDRA HAMACHER und NIELS ECKSTEIN
Resistenzmechanismen von Tumoren gegen Platinkomplexe: Neue Drug Targets und diagnostische Marker 249

MARGARETE BAIER
Sicherheit und Kontrolle im pflanzlichen Kraftwerk – Beiträge zur Regulation des plastidären antioxidativen Schutzsystems 263

SEBASTIAN S. HORN, REBEKAH E. SMITH, and UTE J. BAYEN
A Multinomial Model of Event-Based Prospective Memory 275

Philosophische Fakultät

Dekanat 287

Neu berufene Professorinnen und Professoren 289

ULRICH VON ALEMANN (Dekan)
Wissenschaft. Leben – Die Philosophische Fakultät als tragende Säule von Lehre und Forschung 293

MICHAEL BAURMANN
Soziologie des Fundamentalismus: Der Ansatz der sozialen Erkenntnistheorie 301

AXEL BÜHLER und PETER TEPE
Kognitive und aneignende Interpretation in der Hermeneutik 315

ROBERT D. VAN VALIN, JR.
Universal Grammar and Universals of Grammars 329

GERD KRUMEICH
Nationalsozialismus und Erster Weltkrieg – Ein Forschungsprojekt des Historischen Seminars 339

ANNETTE SCHAD-SEIFERT
Heiratsverhalten, sinkende Geburtenrate und Beschäftigungswandel in Japan 359

KARL-HEINZ REUBAND
Rauchverbote in Kneipen und Restaurants. Reaktion der Bürger und der gastronomischen Betriebe – Das Beispiel Düsseldorf 373

Wirtschaftswissenschaftliche Fakultät

Dekanat 383

GUIDO FÖRSTER (Dekan)
Situation und Perspektiven der Wirtschaftswissenschaftlichen Fakultät 385

WINFRIED HAMEL
Autonomie des Unternehmens – ein frommes Märchen 395

ULRIKE NEYER
Die Verzinsung der Mindestreserve und die Flexibilität der Geldpolitik im Eurogebiet 405

Juristische Fakultät

Dekanat 421

Dirk Looschelders (Dekan)
Situation und Perspektiven der Juristischen Fakultät 423

Nicola Preuss
Die Reform der Juristenausbildung unter den Rahmenbedingungen des reglementierten Rechtsberatungsmarktes 429

Klaus-Dieter Drüen
Steuerliche Förderung von Wissenschaft und Forschung 443

Christian Kersting
Informationshaftung Dritter: Vertrauen auf Verlässlichkeit 457

Jan Busche, Anette Traude und Johanna Boeck-Heuwinkel
Herausforderungen und Chancen bei der Sicherung und Verwertung von „Intellectual Property" durch die Hochschulen – Der Düsseldorfer Weg 471

Zentrale wissenschaftliche Einrichtungen der Heinrich-Heine-Universität Düsseldorf

Humanwissenschaftlich-Medizinisches Forschungszentrum Zur Diskussion gestellt: Stammzellforschung

Johannes Reiter
Menschenwürde oder Forschungsfreiheit? 487

Dieter Birnbacher
Ist die Stammzellforschung unmoralisch? 495

Gesellschaft von Freunden und Förderern der Heinrich-Heine-Universität Düsseldorf e.V.

Othmar Kalthoff
Jahresbericht 2007 503

Private Stiftungen für die Heinrich-Heine-Universität Düsseldorf

Christoph J. Börner und H. Jörg Thieme
Die Schwarz-Schütte-Förderstiftung für die Wirtschaftswissenschaftliche Fakultät 507

Sonderforschungsbereiche der Heinrich-Heine-Universität Düsseldorf

Jean Krutmann und Fritz Boege
Der Sonderforschungsbereich 728 „Umweltinduzierte Alterungsprozesse" 517

Peter Westhoff
Wie Zellen verschieden werden – Der Sonderforschungsbereich 590 531

Graduiertenkollegs der Heinrich-Heine-Universität Düsseldorf

REGINE KAHL
Das Graduiertenkolleg 1427
„Nahrungsinhaltsstoffe als Signalgeber
nukleärer Rezeptoren im Darm“ 545

Graduiertenausbildung an der Heinrich-Heine-Universität Düsseldorf

CHRISTIAN DUMPITAK, LUTZ SCHMITT und DIETER WILLBOLD
Die NRW-Forschungsschule BioStruct – Neue Wege interdisziplinärer
Graduiertenausbildung an der Heinrich-Heine-Universität Düsseldorf 555

Nachwuchsforschergruppen an der Heinrich-Heine-Universität Düsseldorf

DANIEL SCHUBERT
Epigenetische Kontrolle der Pflanzenentwicklung 565

**Kooperation der Heinrich-Heine-Universität Düsseldorf
und des Forschungszentrums Jülich**

KARL ZILLES
Medizin im Forschungszentrum Jülich 579

KARL-ERICH JAEGER und MANFRED KIRCHER
Der Cluster für Industrielle Biotechnologie – CLIB^{2021} 601

**Ausgründungen aus der
Heinrich-Heine-Universität Düsseldorf**

JOACHIM JOSE, RUTH M. MAAS und GUNTER FESTEL
Autodisplay Biotech GmbH – Entwicklung von maßgeschneiderten
Ganzzellbiokatalysatoren und *small protein drugs* 611

**Zentrale Einrichtungen der
Heinrich-Heine-Universität Düsseldorf**

Zentrale Verwaltung

SÖNKE BIEL
Hochschulstandortentwicklungsplanung 625

Universitäts- und Landesbibliothek

IRMGARD SIEBERT
Elektronische Medien in der Informationsversorgung der Universitäts- und
Landesbibliothek Düsseldorf 639

Zentrum für Informations- und Medientechnologie

ELISABETH DREGGER-CAPPEL und STEPHAN OLBRICH
Erneuerung der Server- und Speicherinfrastruktur am ZIM –
Basis für zentrale Dienste zur dezentralen IKM-Versorgung 653

Sammlungen in der Universitäts- und Landesbibliothek Düsseldorf

JUDITH VOLLMER und MAX PLASSMANN
40 Jahre „1968“ – 30 Jahre Studierendenstreik 1977/1978.
Studentischer Protest im Spiegel der Plakat- und Flugblattsammlungen des
Universitätsarchivs Düsseldorf 669

GISELA MILLER-KIPP
Die Sammlung „Janusz Korczak“ der Universitäts- und Landesbibliothek
Düsseldorf und ein Versuch, Janusz Korczak als „Klassiker“ der Pädagogik zu lesen 687

RUDOLF SCHMITT-FÖLLER
Die Flechtheim-Sammlung der Universitäts-
und Landesbibliothek Düsseldorf 697

Geschichte der Heinrich-Heine-Universität Düsseldorf

ULF PALLME KÖNIG
Die Gründungsgeschichte der Juristischen Fakultät
der Heinrich-Heine-Universität 723

SVENJA WESTER und MAX PLASSMANN
Univ.-Prof. Dr. Hans-Joachim Jesdinsky und die
Einführung der Medizinischen Statistik an der Universität Düsseldorf 727

Forum Kunst

JÜRGEN WIENER
Architektur, Stadt- und Landschaftsplanung der Heinrich-Heine-Universität:
Eine Bestandsaufnahme 743

Chronik der Heinrich-Heine-Universität Düsseldorf

ROLF WILLHARDT
Chronik 2007/2008 775

Campus-Orientierungsplan 787

**Daten und Abbildungen aus dem Zahlenspiegel
der Heinrich-Heine-Universität Düsseldorf** 793

Autorinnen und Autoren 805

SEBASTIAN S. HORN, REBEKAH E. SMITH, and
UTE J. BAYEN

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 Leiman (1975).
[4] Cf. Einstein and McDaniel (1990).

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 capacity[8] 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).

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).

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 $C_j, j = 1, \ldots, J$ 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:

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

The probability of an internal state is described with independent parameters $\theta_1, \ldots, \theta_s$ 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).

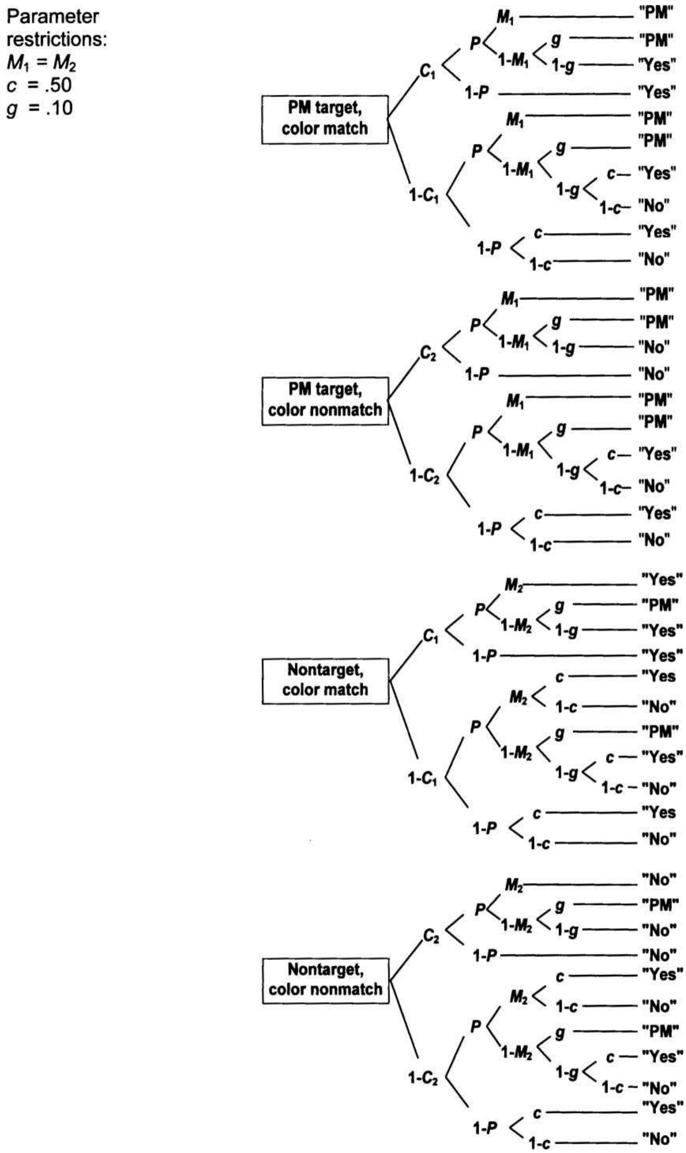

Figure 1: The multinomial processing tree model of event-based PM for three responses. PM = prospective memory; C_1 = probability of detecting a color match; C_2 = probability of detecting that a color does not match; P = preparatory attentional processes; M_1 = probability of detecting that a word is 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.

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).

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

[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).

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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