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The Time Course of Negative Priming

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Dissertation

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1 Introduction

Theoretical life in psychology seemed just a forever-long sequence of dichotomies.
(Newell, 1994)

The present thesis reports on an interdisciplinary attempt at explaining the negative priming effect, a characteristic of selective attention, by a combination of behavioral fundamental research, neuroimaging studies, theoretical psychology and computational modeling. The negative priming effect is one of a very few measures for ignoring. It is revealed as a slowing down of responses to stimuli that were ignored recently as compared to those that are new. Since the discovery of the negative priming effect in 1966 a vivid debate on the cognitive mechanisms underlying the deceleration has evolved, without arriving at a conclusive consensus.

Over the years, a large number of negative priming experiments have been conducted, mostly focusing on a special aspect of the effect by the use of a unique paradigm. Regrettably, the results of each of these studies show a unique pattern as well. Only the bare slowing of responses to previously ignored stimuli is found in most of the experiments, but virtually any manipulation of a paradigm also affects negative priming.

In the introduction we will explain the negative priming phenomenon in section 1.1, giving a condensed overview of the exhaustive presentation of the field of negative priming in chapter 2. We then expound the importance of computational modeling for theoretical psychology in section 1.2. The structure of the thesis is presented in section 1.3 which also describes our research on negative priming as a whole. Finally, in section 1.4 we will conclude the introduction by listing the original contributions included in this thesis.

1.1 Negative Priming

Selective attention enables goal-directed behavior despite the permanent, immense input to the sensory system. The downside of this ability involves the problem of how information is ignored. Contradicting early speculations of an active attending and passive ignoring, a special situation revealed the active nature of ignoring. In the original experiment by Dalrymple-Alford and Budayr (1966), subjects had to process lists of Stroop tasks. While in the original Stroop task no systematic repetition of color and color words was implemented, these authors composed the stimulus cards in a special way, namely the ignored meaning of a color word always became the to be named color in which the next word was shown on some of the lists, on others there was no relation between two succeeding words. The experiment showed that people were slower in responding to the related lists compared to unrelated stimulus colors. Even if the semantic meaning of the words has been ignored, it must have entered the cognitive system as it showed the characteristic interference.

Since then, several standard negative priming paradigms have emerged, each featuring a certain dimension on which priming happens, e.g. the identity of stimulus objects or their location on the presentation screen. The set of stimuli also varies enormously, e.g. pictures, shapes, words, letters, sounds, colored dots. The common denominator of all paradigms is the classification of stimuli in targets that have to be attended to, and distractors that are to be ignored. Stimulus repetitions are considered in dependence of the role of the repeated object as target or distractor in two related trials. Variations of this basal setting include the manipulation of experimental parameters like the time between two related trials, the number of distractors from zero in some trials to multiple over the entire experiment, and the saliency of the distractor. For a detailed listing of the sometimes contradictory results, see section 2.3.

Because of the controversial nature of the negative priming effect, a variety of different theoretical accounts have been developed. But until now none of the theoretical accounts is able to explain all aspects of the negative priming effect, they all have their strong points as well as their shortcomings. All theories assume different mechanisms to be responsible for negative priming. In order to clarify the situation of diverging explanatory accounts, the time course of negative priming is crucial. The mechanisms postulated by the different theories act in different stages of trial processing.

1.2 Computational Modeling of Negative Priming

The theories to explain negative priming can be categorized roughly as memory-based and activation-based accounts. The first group assumes the memorization of a trial and eventually a retrieval of the information in the next trial. The latter group assumes negative priming to be caused by interference of trial processing with persistent activation from former trials. Both directions produced a variety of small branches, many limited to a single appearance in order to explain a certain, singular pattern of results. But due to the lack of comparability and concreteness, there is no solution of the debate on the level of argumentative theories in sight.

In the face of such a sensitive phenomenon it is understandable that no comprehensive explanation has been found so far. Because a satisfying theory should be less complex than the data it explains, it seems reasonable to focus on the interaction of the underlying causes instead on ad hoc defined data features. However, a main reduction of complexity is already achieved by the design of experiments. Nevertheless, a theoretical approach is based on the assumption that the complexity of experimental data can be further reduced by identifying repeating patterns in the data. Our first attempt, the implementation of a simplified but still biologically motivated model of target selection has proven too simple by our experiments. Although it provided us with a tangible account of several dependencies of negative priming. A crucial point in the specification of mechanisms producing negative priming seems to be the exact time course of processing a trial where a previously ignored stimulus has to be attended in comparison with the processing of an unprimed stimulus. Therefore, we faced the problem to reveal temporal information about negative priming.

A first step in that direction is already our simplistic computational implementation as described by continuous nonlinear differential equations which themselves show a characteristic time course. In order to test the validity of the model we designed several experimental paradigms according to the objective of making statements about the inner temporal structure of a negative priming trial. Some of the experiments recorded EEG data which has shown to be a beneficial tool in identifying systematic differences in trial processing, both spatially and temporally. For two experiments we developed techniques to record additional time makers during trial processing, making it possible to temporally localize the emergence of reaction time effects. In order to tackle the problem of diverse paradigms and the incomparability of theoretical accounts, we designed a computational framework for perception based action selection by means of physiologically justified building blocks which each obey a biologically plausible dynamics.

Despite all concise and generally understandable theories that seem to have identified the causes of an observed phenomenon, it is very important to keep in mind that psychological fundamental research uses statistical properties of experimental data in order to interprete human behavior. On the one hand, behavioral experiments tend to produce largely varying results, caused by the complexity of the human cognitive system. On the other hand, the interpretation of results is usually not unambiguous. Both aspects provide a base for the arduous and controversial discourse that is necessary for clarifying a certain psychological phenomenon.

One possibility to proceed in the discussion is to solidify theories by mapping their assumptions on measurable processes in the brain, thereby eliminating arbitrariness of the respective interpretations. A second way is to computationally implement theories. Clearly, the obtained implementation inherits the freedom of interpretation from the underlying theory. Yet, the implementation adds further degrees of freedom. But the benefits of an implementation are obvious. It eliminates the risk of misinterpretation, as the source code can be made available for other research groups interested in working with the model instead of leaving them with wordy descriptions. A computational model may provide links to biological data, all the more if it is based on naturally observable processes.

Nevertheless, certain aspects have to be remembered when arguing on the level of implementations. In order to reproduce the observed results, most models have to undergo a precise fitting of parameters, which is also a very subjective process. Therefore, great care has to be taken of the distinction between results due to parameter fits and extrapolations by the internal dynamics of the model itself. A different way to benefit from a computational model is to analyze the structural result after fitting, which carries a formalized version of the fitted data. Or, in the words of Hintzman (1991): *The measure of a model's value lies not in its ability to fit data, but in how much we can learn from it.*

We will comply with the necessity of quantification in two ways. First we will take up a single theory of negative priming, i.e. the imago semantic action model described in section 2.4.7, and build a minimal model producing realistic effects on the basis of the postulated mechanisms, see chapter 3. A detailed implementation was performed in close interaction with the originator of the theory. The presence of the cognitive representation of a certain object is modeled by a single variable, by which we obtain a rather clear dynamic system which is able to deal with realistic stimulus sequences and generates artificial reaction times. In chapter 6 we will show how the model can be extended to generate hypotheses in a more complex paradigm. The generalized model enables us to resolve contradictions arising in the initially attempted modeling approach. This is to be considered as a success of the modeling process, as we are able to falsify an essential assumption of the original theory by means of a straightforward implementation.

The second computational approach is more ambitious with respect to the discussion about the applicability of the theories of negative priming in specific situations. We build a computational model comprising most of the mechanisms suspected to play a role in the neural processing in negative priming. The outcome is not only a meta-model for negative priming, termed General Model, but in itself a simplified model of the brain as a framework for action selection based on perception. We addressed the tradeoff between biological realism and understandability by modeling each assumed mechanism separately but keeping the internal dynamics of each of the corresponding layers very simple by taking over the dynamical framework of our first model.

1.3 Thesis Overview

The present thesis will describe our multi-level approach to reveal the temporal structure of the negative priming effect. Accompanied by computational modeling, we run sophisticated psychological experiments and record and analyze EEG data. We will start with an overview of the phenomenon of negative priming in chapter 2.3 by reviewing the literature for behavioral results and theoretical explanations of the effect.

Based on one of the theoretical accounts introduced in chapter 2.3, namely the Imago Semantic Action Model, see section 2.4.7, we will implement our first computational model for negative priming, the ISAM. The basics of the modeling approach and the implementation will be the first part of chapter 3. The second part will be devoted to testing the ISAM by deriving predictions and reproducing several effects related to negative priming.

Adapting the voicekey paradigm described in section 2.2, we will describe an EEG experiment in chapter 4 that replicates findings from one of the few studies on event-related potentials related to negative priming. Beforehand we will give a detailed introduction to EEG recordings and the corresponding data analysis and thoroughly review hitherto existing findings of EEG correlates of negative priming.

During the preoccupation with EEG data analysis, we came upon an inconsistency in averaging event related potentials. Chapter 5 introduces our solution to the problem to reconstruct a very noisy signal that additionally is subject to erratic temporal fluctuations. As such a new technique first has to prove its validity in a broad discussion, we limit it in the current thesis to an interlude independent of the remainder.

Due to the additional source of uncertainty in EEG research, i.e. the interpretation of differing event related potentials in the different experimental conditions, we determined ourselves to behavioral experiments and designed a paradigm which requires a button press between stimulus identification and target selection phase which is recorded as an additional reaction time. Chapter 6 describes the model based generation of hypotheses by the ISAM of chapter 3, the paradigm itself and finally the results that locate negative priming in the later part of a trial and that contradict the ISAM all along the line.

After separating the stimulus identification phase, the remainder of a trial still contains the two stages of processing of target selection and response generation. One theory predicts negative priming to be exclusively produced in the response generation phase. Therefore, we constructed a second trial splitting paradigm which now singles out the response generation phase. In chapter 7 we will describe the paradigm, go into expected side effects of the altered paradigm and finally display the results, the devotion of negative priming to the target selection phase of a trial.

Not only the nontrivial extension of our identity based priming paradigm given in chapter 7 to a comparison task, but also the counterevidence for the ISAM by the experiment in chapter 6 made us head for a less rigid computational model. Chapter 8 pictures the result in form of our General Model for negative priming which provides an implementation of each theory and the ability to respond in various different negative priming paradigms. Due to the complexity of the model chapter 8 can only be seen as the general introduction to a new framework which will possibly shed light on the questions why different paradigms produce such diverse result patterns, and how the theories can be compared on a par.

The previous chapters are concluded in chapter 9 which also collects all results and forms a complete picture of negative priming as we can give it by our research. This chapter contains also an outlook on future directions to finally conclude the main body of the thesis. Appended is a listing of experimental data in tables, which were excluded from the according chapters for the sake of readability.

1.4 Original Contributions

All work presented in the present thesis is carried out by a closely cooperating workgroup in the framework of section C4 of the Bernstein Center for Computational Neuroscience Göttingen. The results presented here would not have been possible without this collaboration. My personal contributions are not restricted to modeling but have had an increasing influence also on experimental design, data analysis, interpretation of results, and design of algorithms.

Our main contributions to (but not limited to) negative priming research are listed in the following.

- We developed a simple model for the transient of the firing rate response of an integrate and fire network to constant input by the means of a nonlinear Langevin equation, section 3.1.
- We employed the resulting dynamics to build a minimalistic computational model, section 3.2, reproducing priming effects based on the mechanisms of the global threshold theory, section 2.4.7.
- With the good performance of the model, section 3.3, we quantitatively validated global threshold theory (Schrobsdorff et al., 2007b).
- We adapted our voicekey paradigm, section 2.2 to an EEG recording environment, section 4.4 and replicated some of the very sparse event related potential correlates for negative priming found in a rather different paradigm, section 4.6.
- We confirmed that processing in ignored repetition trials first benefits from stimulus repetition similar to the attended repetition condition, but only later in the trial both conditions diverge due to different demands on cognitive control, section 4.8, (Behrendt et al., 2009)
- We developed sophisticated signal processing methods, sections 5.4 and 5.7, which enhance the averaging of event related potentials, section 5.7.5, and provide a measure for the temporal variation in the processing between two trials, section 5.5, (Ihrke et al., 2008, 2009b).
- We designed an enhanced algorithm for line-of-synchrony detection in recurrence plots which outperforms established solutions, section 5.7.4, (Ihrke et al., 2009a).
- We introduced time markers in addition to the usual reaction time into negative priming paradigms, making it possible to investigate the temporal structure of the mechanisms causing negative priming by means of behavioral measures, section 6.1 and 7.1.
- By applying our technique of recording intermediate time markers, we have shown that the stimulus identification phase of a trial carries no negative priming, but only facilitation in the presence of repeated objects, section 6.6.
- By deriving predictions from our computational implementation of the global threshold theory to the task switch paradigm, section 6.2, we provided strong counterevidence for that theory as predicts negative priming to happen already in the identification phase, sections 6.3 and 6.6.
- We showed that negative priming happens in the target selection phase of a trial, section 7.5, by again isolating a part from trial processing, in this case the response generation phase, section 7.1.

- Finally we implemented a neurophysiological model, section 8.3, of the parts of the brain that are assumed to be involved in processing a priming trial, section 8.2. The General Model is able to cope with various paradigms, section 8.1.1, and implements the behavior assumed by any of the negative priming theories, section 8.1.2.

Although partially not yet published as articles, all points are documented by a series of conference contributions listed on page 162 ff. and are available at

`www.nld.ds.mpg.de/~hecke/research.html`

2 Negative Priming

Priming is characterized by a sensitivity of reaction times to how stimuli have been encountered recently. A reduction of the reaction time, positive priming, is usually observed with repetitions of stimuli or responses and is well-known and experimentally understood (Scarborough et al., 1977). Our object of investigation, negative priming, a slowdown in the reaction time usually in response to previously ignored stimuli, is experimentally less tangible (Fox, 1995). The negative priming effect is sensitive on even subtle parameter changes, which poses many methodological and conceptual challenges, but bears exactly for this reason great potential for applications in research fields such as memory, selective attention, and aging effects.

The following chapter will thoroughly introduce the negative priming phenomenon. After a classification of negative priming and a description of the terminology used in negative priming studies in section 2.1, we will discuss a showcase study to give a feeling for what a negative priming experiment looks like in section 2.2. The diversity of findings concerning negative priming will be shown in section 2.3. Then we will give a detailed listing of theoretical accounts to the negative priming effect in section 2.4.

2.1 A Paradigm to Access Selective Attention

Selective attention is the process of extracting behaviorally relevant information from the environment. The focusing on particular stimuli brings along an ignoring of irrelevant information. The process of ignoring is investigated by systematic variation of irrelevant stimuli. Interesting effects like change blindness, the failure to perceive even striking changes in a visual scene that are not behaviorally relevant (McConkie and Currie, 1996), or inattentional blindness, the apparent insensitivity of the cognitive system to unattended stimuli (Simons and Chabris, 1999), demonstrate impressively that our feeling of perceptual accuracy is not objective.

It is still unclear how the selection of stimuli is done. Two classes of mechanisms are assumed, top-down and bottom-up processes (Anderson, 2001). The first process actively guides the attentional focus by highlighting particular features of current interest. The latter one describes selection due to perceptual saliency. In everyday tasks, both of them interact.

As selection and ignoring are two sides of the same medal, the nature of ignoring is crucial, as distracting information can easily be varied in experiments, and thus gives access to the act of selection itself. Even if early attempts assumed a passive ignoring, empirical evidence for an active process comes from the inhibition of return paradigm (Milliken and Tipper, 1998). A prolonged reaction time is observed if a location which has been in the focus shortly before is required to be attended to.

A general approach to the processing of distracting stimuli is provided by the negative priming paradigm. Negative priming is often considered the most direct approach to assess the selective aspect of attentional processing, as the ignored, distracting stimuli can be proven to be actively processed (Houghton and Tipper, 1994).

Selective attention has to permanently deal with distracting information. Most paradigms we will discuss in the following show two items in each trial. One is to be attended, called the target, while the other one, the distractor, is behaviorally irrelevant and has to be ignored. One such