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Neurodynamical approach to the picture–word interference effect

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Abstract

The aim of this study is to explore the nature of the semantic effects in the picture–word interference paradigm. In particular, we focused on the (a) identity effect, (b) semantic interference effect, (c) semantic facilitation effect, and the semantic facilitation in categorization. Our model is based on integrate-and-fire neurons which are put in a network context featuring modular competition and cooperation at both intra- and intermodular level. A finely tuned balance of competition and cooperation is required to combine the mentioned effects in a coherent framework. We show that the mechanism for categorization must be functionally decoupled from the basic level mechanisms.

Keywords: Picture–word interference effect; Neurodynamic; Integrate-and-fire; Biased competition; Linguistics

1. Introduction

One of the crucial stages when producing speech is the retrieval of the lexical items from the lexicon. The mechanism in charge of such retrieval has been labeled under the term ‘‘lexical selection’’. One of the most used methods to explore the principles governing lexical selection is the picture–word interference paradigm. In this paradigm, participants name pictures while ignoring the presentation of a distractor word. Interestingly, by manipulating the relationship between the picture and the distractor word different effects are observed. For example, naming latencies are slower when the target picture (car) and the distractor word (truck) belong to the same semantic category than when they are unrelated (car–parrot). This Stroop-like effect has been interpreted as revealing the competitive nature of the lexical selection mechanism. Accordingly, the semantic interference effect arises because of the larger lexical competition created by the lexical node of a semantically related distractor (truck) in comparison to a semantically unrelated distractor (parrot) in the course of naming the picture. Moreover, there are also differences among unrelated distractors. An existing word (parrot) causes more distraction than a non-word (spft) or a string of letters (xxx). These effects arise because the lexical representation of the related distractor receives activation from two sources: (a) the presentation of the distractor word itself; and (b) the semantic representation of the target picture.

In such framework one would predict that any semantic relationship between target and distractor should lead to semantic interference. However, this is not the case. For example, when participants have to categorize the target picture rather than to name it (e.g., say vehicle when presented with the picture of a car), a semantically related distractor (truck) facilitates performance in comparison to an unrelated distractor (parrot).

The polarity of the effects produced by semantically related distractors depends also on the asynchrony between the presentation of the target picture and the distractor word. When the two stimuli are presented simultaneously or in close time vicinity (e.g., 200 ms apart) semantic

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interference effects are observed in picture naming. However, if the distractor is presented about 500 ms before the target picture, the semantic interference turns into semantic facilitation. That is, naming latencies are faster when the distractor is semantically related to the target picture than when it is unrelated.

The complex pattern of results observed with this paradigm suggests that we need to postulate a more enriched conceptual/lexical structure to capture the change in the polarity of the semantic contextual effects. Also, it highlights the possible contribution of attentional factors to the effects produced by distractor words. Furthermore, at present we do not have a satisfactory computational model that accounts for such a pattern of results.

In the present study, we gain insights about this issue by developing a dynamic model that, using a computational neuroscience perspective, considers the neuronal and cortical mechanisms underlying the behavior of the picture–word interference paradigm. Neurodynamics, described at the level of spiking and synaptic activity, are used to provide a quantitative formulation for the dynamical evolution of single neurons, neural networks, and coupled hierarchical modules of networks. The structure is organized within the general framework of the biased competition and cooperation hypothesis for attention, working memory and reward processing [10], in which multiple activated populations of neurons interact with each other in a hierarchical way. Neural populations which are combined to model an individual brain structure (e.g., a cortical area) engage in competitive and cooperative interactions with each other, trying to represent their input in a context-dependent way (emergent network effects). However, biased competition and cooperation networks often consist of several model areas. External inputs from one model area bias the internal competition and cooperation in favor of specific neurons. By this bias, each model area forms a context or 'top-down hypothesis' in the framework of which the dynamics of the other areas are guided. The operation of biased competition and cooperation networks in general can be imagined as a negotiation process between different specialized experts: Each model area tries to represent one aspect of the environment. Each representation alone is insufficient to deal with the complexity of the environment. However, the areas bias each other and mutually guide their internal dynamics until a maximally coherent state is reached, which then forms a global representation of the environment [2].

There are several connectionist symbolic models that have tried to account for such a complex pattern of results [9]. However, these models have had a partial success and some of their assumptions have been shown to be incorrect (see [4,5]). Our modeling approach is different than those used before by giving a neurodynamical account of the semantic contextual effects observed in the picture–word interference paradigm. The nonlinear dynamics underlying the word–picture interference are carefully studied by using mean-field and spiking neuron simulation techniques in a biologically realistic approach and several experimentally observed behavioral effects are integrated in a unifying theoretical framework.

2. Model description

We model four different effects which are observed within the picture–word interference paradigm. As representative stimuli, we use truck, parrot, spft, xxx (distractor words) and car (distractor word and target picture). In addition to that, the category vehicle is needed as response. Experimental evidence suggests that the combination car (target) and car (distractor) yields the fastest reaction time (identity effect), followed by car–xxx, car–spft and car–parrot (see [4,7]). Due to the semantical interference, car–truck has the slowest reaction time, whereas the categorization task of the combination car–truck can be put in between car–spft and car–parrot in terms of reaction time. Thus, the categorization task is significantly faster than the corresponding picture naming task of car [8]. In addition to that, we address the semantic facilitation effect of different stimulus onsets [1,6].

The dynamics of our model are created by detailed neural and synaptic descriptions which contain data of biophysical measurements to yield a highly realistic behavior. The basic framework consists of fully connected excitatory and inhibitory neurons. They are described by non-linear integrate-and-fire equations and synaptic receptor channels for AMPA, NMDA and GABA receptors using the same mathematical formulation as in [3]. The network receives external input from the surrounding matter unselectively corresponding to the spontaneous firing rate of the cortex and from specific external inputs. The network structure is adjusted due to the experimental paradigm. Our model consists of two modules, which are fully connected internally, contain both selective and non-selective neurons (NS) and are governed by low range inhibition mediated by the inhibitory pools (IH) (Fig. 1). Each of them contains selective representations of lexical items. One module is used for the basic-level items (car, truck, parrot, spft, xxx), the other one for the category (vehicle). Each item is represented by a population of numerous neurons. The structuring of the populations and the connections between them is done by different connection strengths between the neurons. According to the Hebbian paradigm, neurons of the same population are activated frequently in a correlated manner and thus are strongly interconnected. The populations themselves are interconnected according to the relationship between the items, so that more related items share stronger connections than less related ones. These connections are built up by learning and interaction with the environment. We treat these as free parameters in our analysis, although we recognize the linguistic background that underlies the process of building up these connections. Furthermore, we see the representation of a single item not as confined to the