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Modelling the Stroop effect: A connectionist approach

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Abstract

A connectionist model, which simulates the operation of prefrontal circuits during Stroop task is proposed. The Stroop test has traditionally been used as a measure of cognitive inhibition. The task is to inhibit an over-learned, habitual response (i.e., reading color words) in favor of an unusual, novel requirement (i.e., naming incongruously printed colors of color words). The longer durations in completing the task indicate an inability to inhibit habitual but contextually inappropriate response tendencies, which is suggestive of a prefrontal dysfunction. The connectionist model is designed adapting artificial neural networks (ANNs) in such a way that each ANN corresponds to a particular neuroanatomic component of the prefrontal circuit which is likely to take part in the execution of the Stroop task. The ability of the proposed model to simulate the normal and the abnormal performance on the Stroop task is tested. The simulation results show that the model is consistent with the clinical data.

Keywords: Stroop test; Prefrontal cortex; Artificial neural network; Automatic response inhibition

1. Introduction

The Stroop test is one of the popular tests of executive functions involving cognitive inhibition [7], more specifically resistance to interference or ability to inhibit inappropriate automatic response tendencies [64]. First published in 1935 by Stroop himself [57], the test had been established as a clinical and research tool in order to probe frontal lobe functions associated with selective attention in neuropsychology [43]. The ability to process one feature while disregarding another is the fundamental property of selective attention. In daily life, it is required to inhibit the irrelevant or interfering stimuli and to focus on the currently relevant one in the environment. The Stroop test is used to explore the limitations of inhibitory process on irrelevant responses. The test, as briefly stated, consists of color words that are printed in different colors that the words denote. When the task is to name the color of the word instead of reading it, the more automatic response tendency of reading should be inhibited. This inhibitory process is associated with the executive or modulatory functions of the frontal lobe, whereas reading color words, a response strongly associated with the stimulus, is over-learned and habitual, thus it is a process thought to be executed by the basal ganglia (BG) structures [45].

Inspired by the diverse work in the literature on the role of the frontal lobes during Stroop task performance which has been accumulated by the lesion analysis studies of the clinical cases and functional imaging studies in normal subjects (for a review see [46,52]), a model simulating the interaction of the different parts of the prefrontal cortex (PFC) is proposed. The influence of each part of the PFC on the others is believed to trigger the initiation of specific subtasks in order to accomplish the Stroop task. The objective of this work is to propose a connectionist network model which can be used to illustrate how the higher order cognitive processes come into play during

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Stroop test. Accordingly, putative neuronal substrates that are likely to underlie these cognitive processes are investigated and the model is established on the basis of the functional interaction of these neuronal modules rather than the interactions of the individual neurons at the physiological level. This approach is tenable as there is still no crystal clear theory of how high-level cognitive processes emerge as the participating neurons interact [16].

The proposed model is constructed using artificial neural networks (ANNs). Below, we are going to discuss the neural structures associated with the Stroop test, introduce the proposed connectionist model and finally present the simulation results. There are previous attempts to simulate the Stroop task, [17,18,51], where only the duration of the interference task is modelled. We took a more direct approach and attempted to simulate various test indices as they are used in clinical practice (i.e., the duration of the interference task, the number of committed errors and the number of spontaneous corrections).

2. Frontal circuits for Stroop task

Based on its different anatomical connectivity patterns and functional nuances PFC is traditionally subdivided into dorsolateral (Dl) and ventromedial (Vm) sectors [45,5]. Executive functions, such as planning, abstraction and mental flexibility are commonly associated with Dl sector. The selective lesion of the Dl sector gives rise to so-called dysexecutive syndrome. On the other hand, the Vm deals with emotional control and comportment, selective lesions of which result in the disinhibition syndrome. These latter patients are behaviorally disinhibited, socially inappropriate, impulsive and display difficulties controlling their drives (i.e., gluttony and sexual misdemeanor). A subset of such patients who display decision making difficulties in social settings and accordingly cannot maintain a gainful employment despite having normal neuropsychological test scores including the traditional tests of executive functions has recently been named as suffering from “the acquired sociopathy syndrome” by Eslinger and Damasio [21].

While it is evident that “inhibition” as a general concept is a function of the PFC, it seems that Dl and Vm are dealing with inhibition in a contextually relevant way. It is likely that while Dl takes part in inhibitory control of attentional selection in tasks such as the Stroop test, Vm guides decision making through emotional and behavioral inhibition in social settings [32]. There is growing evidence in the literature that indicates right more than left part of inferior or opercular portion of the Dl (Brodmann areas 44, 45 and 47), that is the right-sided analog of Broca’s area, is in charge of inhibitory control in complex attentional tasks such as the Go–NoGo and the Stroop where the interference of the inappropriate stimuli should be dealt with [12,38,40,44,54,59].

Furthermore, it is reasonable to conceive the PFC as modulating the ongoing activity through exerting an inhibitory influence on BG and redirecting the organism from the automatic or habitual response channels to the novel, task-relevant one. After the establishment of parallel fronto-striatal circuits hypothesis [2,3], PFC has been further subdivided parsing out the anterior cingulate cortex (aCC) from Vm sector and naming the latter as the orbito-frontal loop (OF). The OF is roughly the equivalent of the Vm, while the aCC is responsible for intentional behavior and motivation, the lesion of which gives rise to abulic or apathetic state [60]. Relevant to our modelling, as evidenced by the event-related potentials (ERP) and functional magnetic resonance imaging (fMRI) studies the aCC is also implicated in conflict and error detection [58,42,27,62,61] in tasks such as Stroop, as will be discussed in detail below.

Goal-directed behavior is the fundamental function of the PFC [23]. Moreover, the ongoing activity relevant to the goal-directed behavior has to be actively guarded against the competing stimuli. Thus, the attempt to interfere must be inhibited in order to enable the behavior to reach its goal on time (i.e., resistance to interference). If a behavioral pattern is associated with the same successful result in a time course, than this behavior is called habitualized and freed from prefrontal control. In other words, in order to deal with a novel situation, the PFC takes over and inhibits automatic response tendencies that are mediated chiefly by the BG, but for the routine processes this extra effort is not needed and the BG can effectively deal with the usual or accustomed stimuli.

The BG are a collection of subcortical nuclei including caudate nucleus, putamen, nucleus accumbens, globus pallidus, substantia nigra and subthalamic nucleus [49]. The BG had been associated with motor control, since dysfunction of them results in some forms of movement disorder such as Parkinson’s and Huntington’s disease. The recent anatomical, neuropsychological and functional imaging studies indicate that the BG are also involved in regulating higher executive functions [11]. This may be due to massive connections with the PFC. Alexander et al. indicate that the BG participate in five parallel closed loops with cerebral cortex [3]. They include Dl, lateral orbital and anterior cingulate circuits which are also the complex loops, human analogs of which are implicated in executive, compartmental and motivational functions, respectively [60].

The BG are important for stimulus–response associations and habits. In the literature there is also an interesting claim that the BG use the fronto-cortical–striatal loops to train the cortex to produce a learned motor response when a cue about the stimulus is presented [47,39]. Repetition of a behavior causes automaticity which requires minimal cognitive monitoring. The process guiding habits occur largely covertly. People should not be reflecting on their behavior during habitual performance. According to Graybiel automated behavior is an attribute of the BG and this explains the BG lesioned patient’s difficulties in performing sequential actions [29]. Parallels from the animal literature come from an experiment by Jog et al.

which states that the observed firing patterns of neural ensembles recorded in the sensorimotor striatum of the rat during the acquisition of habits remained stable during the subsequent performance of the same task [34] suggesting that the BG neurons may be responsible for representation of habitual acts. There are also experimental studies with humans exploring the role of BG in habit learning [39,35].

There are several electrophysiological and neuroimaging studies to delineate the active regions of the cortex during the Stroop test [48,6,63,10,9,50,41,12,58,30,1,4]. These studies particularly emphasize the activation at the right aCC and the right Dl, along with some other regions of the PFC. In order to figure out which region takes part in directing attention to task-relevant information, Banich and Milham have conducted fMRI study which revealed that the Dl PFC is more active as compared to the aCC [4]. According to Posner and DiGirolamo, the aCC is responsible for "attention to action", i.e., aCC accomplishes the control job [53]. On the other hand, Carter et al. claim that the aCC is responsible for detecting the response conflict, whereas Dl PFC takes part in cognitive control [42,14].

In an environment where numerous stimuli coexist, as in normal daily life, in order to accomplish a specific task, one has to discriminate and focus on the task-relevant ones. Furthermore, one has to monitor the relevance of his actions in accordance with the goal. The electrophysiological and neuroimaging studies show that the aCC and parts of the Dl are both active during such action monitoring. In the ERP literature, the negative wave which is observed immediately after an error during choice reaction time tasks is called error-related negativity (ERN/Ne) whose generator is believed to be aCC [27,25,33]. The explanations given for the causality of the generation of the ERN/Ne are controversial. While one group claims that ERN/Ne is related to error detection [58,27,22], other groups assert its emergence in association with conflict detection [42,62,61,10,9,14,13,26]. According to error detection viewpoint, the real response is compared to internal goal and in the case of disagreement error signal is generated. This error signal notifies a compensating system in order to take necessary precautions for correcting the error [19]. On the other hand, the conflict detection viewpoint claims that the ERN is generated whenever there is a conflict between responses. So that it is a warning sign for the organism to allocate attentional resources appropriately for the solution of the conflict correctly.

3. Description of the Stroop test

Stroop test was first proposed to illustrate selective attention within the realm of experimental psychology [43] and only later became an instrument for clinical neuropsychology, students of which have developed numerous versions of it so far, although the main objectives remain the same [43,46]. We chose the Victoria version [56] for our purpose, for it is the one of the two versions for which the published norms are available for Turkish subjects. We must note however that this is not the most common version used in research and published work.

The material for this version is three cards containing six rows of four items. Four color words—red, blue, green and yellow—are printed in black on the first card. The second card contains colored dots in above four colors. The last card has color words printed in non-matching colors. Accordingly, there are three trials. On the first trial, the subject is requested to read the black-print color words. For the second trial, the task is to name the color of the dots. Finally, on the third trial, which is also called the interference trial, the subject is requested to name the colors, ignoring what is written as the words.

The main objective is to perform the tasks for each trial as quickly as possible. The first and second trials are used as indices of word reading and color naming speeds, respectively. The first trial is also used for establishing an automatic response tendency. The duration of the interference trial takes normally up to three times longer than the first trial [64,46]. Also scored in some versions are the number of errors and corrections. An error occurs, when the subject reads the word, instead of naming its color and moves the next in the row. A correction on the other hand is recorded when the subject noticing her fault corrects herself before moving the next word in the row.

The normative data for the Victoria version come from the study of Spreen and Strauss [56].These are 86 healthy older subjects with a mean education of 13.2 ± 3.1 years. Our reference values have been the means of 19 subjects who were in the age group 50–59 ages. The durations of first and third cards are given along with number of errors in the third card: 16.58 ± 3.34 and 28.9 ± 7.62 s and 0.42 ± 0.77 errors, respectively. In the Turkish study [37] 395 subjects were divided into two education (5–8 years and 9 years and over) and two age groups (20–54 years and 55–82 years). Only the durations are given for all three cards. The author reportedly declined to include the error score, having seen that it was not useful for studies in the normal subjects, after a series of statistical computations. The means of the higher educated-younger group are similar to those of Spreen & Strauss (S&S) values: 12.32 ± 2.71, 8.82 ± 1.76 and 26.38 ± 12.29 s for the three cards, respectively. Aging affects the performance prolonging the time to complete the interference task [20,37]. This is probably due to the convolutional effects, which are expected to involve first and foremost the PFC [24]. Faulty performance with aging necessarily comes with an increased number of corrections. Hesitancy arising from ineffective inhibitory control vis-à-vis reading vs. naming conflict results in the prolongation of the duration, while the time spent for the corrections further prolongs it. Another faulty performance might be the impulsive reading, ignoring the required task of naming and this might be reflected by the increased number of errors sometimes even within the accepted time limits. Impulsivity is known to impair inhibitory control, such as the Stroop effect [15].

Although for scoring purposes the number of errors and corrections obtained by the model will be reported, for conveniency we are going to focus our discussion on the results of the time durations for the interference task (i.e., interference time), since this is the common measure which was reported in both the original study and its Turkish adaptation and also because it is the most commonly used measure for the Stroop performance both in clinical and experimental literature.

4. The connectionist model

We attempted to model the above-mentioned neural structures and processes by ANNs, to achieve simulation results in agreement with the human data. We have taken into account the subtasks that we considered as mutually interacting in the performance of the Stroop task. These are shown in Figs. 1 and 2. The modules drawn are not the real physiological-anatomic analogs, but rather an approximation of the prefrontal system in functional terms.

In Fig. 1, the blocks corresponding to the sensory and motor networks are always on duty, while the other blocks take turn according to the relevant cognitive process. As word reading is over-learned and habitual, the blocks that take turn during this task are only the attention directing and habitual response modules (see Fig. 1a), whereas for color naming the inhibition of the word reading tendency is needed and during this course an error detection module must also be on duty. These two new modules are shown in Fig. 1b.

During the test, the subject must focus on the task-relevant feature, i.e., color during the color-naming task. This function has been enabled by implementing an attention directing module. According to Mesulam directed attention is subserved by a large-scale neurocognitive network which is located in the right hemisphere with an "epicenter" located anteriorly (i.e., the frontal eye field—FEF), major function of which is to choose and to sequence exploratory and orienting responses [45]. Several neuroimaging studies showed the activation of right Dl, which includes the FEF during attention monitoring tasks. The aim of attention directing module is to direct the related brain regions to task-relevant information. A simple mechanism composed of two units, each dedicated to one task, is considered for attention directing module. We think that this is quite suitable for the Stroop test, since the word reading and the color-naming tasks used in the test are routine tasks of normal daily life, their internal representations are modelled by predetermined connection weights of the units. When the task is presented, it is expected that the task-related unit causes the activation of the corresponding sensorimotor network in the model. Since the word reading is the habitual one in daily life, its internal representation is weighted with a matrix to emphasize it over color naming. So, when the task is color naming, the word reading unit also generates an output (i.e., the interference). However, activation of color-naming unit activates the inhibition module to take its turn and inhibits the activation of the word reading unit.

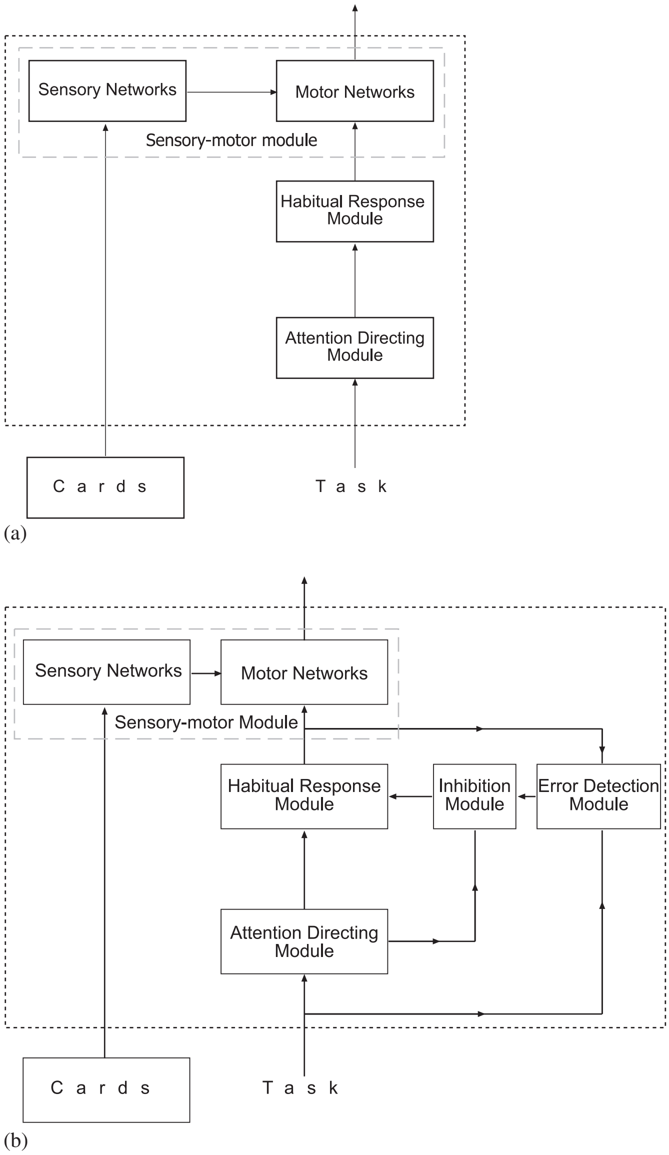

Fig. 1. Modules corresponding to the processes during the Stroop test: (a) modules for word reading and (b) modules for color naming.

In the model, the function of the inhibition module is done by a Hopfield network. We consider this inhibition as analogous to the prefrontal apparatus for cognitive inhibition. As discussed earlier, frontal opercular regions, right more than left, might fit in this role. The role of the Hopfield network is to generate a sufficiently large output in order to inhibit the output of the biased word reading unit. In order to perform the inhibition, the output of the inhibition module must be higher than the output of the word reading unit. Hence, in the inhibition module, the output of the Hopfield network is summed up to generate the output that is capable of inhibition. The continuous Hopfield network with two units is designed for this

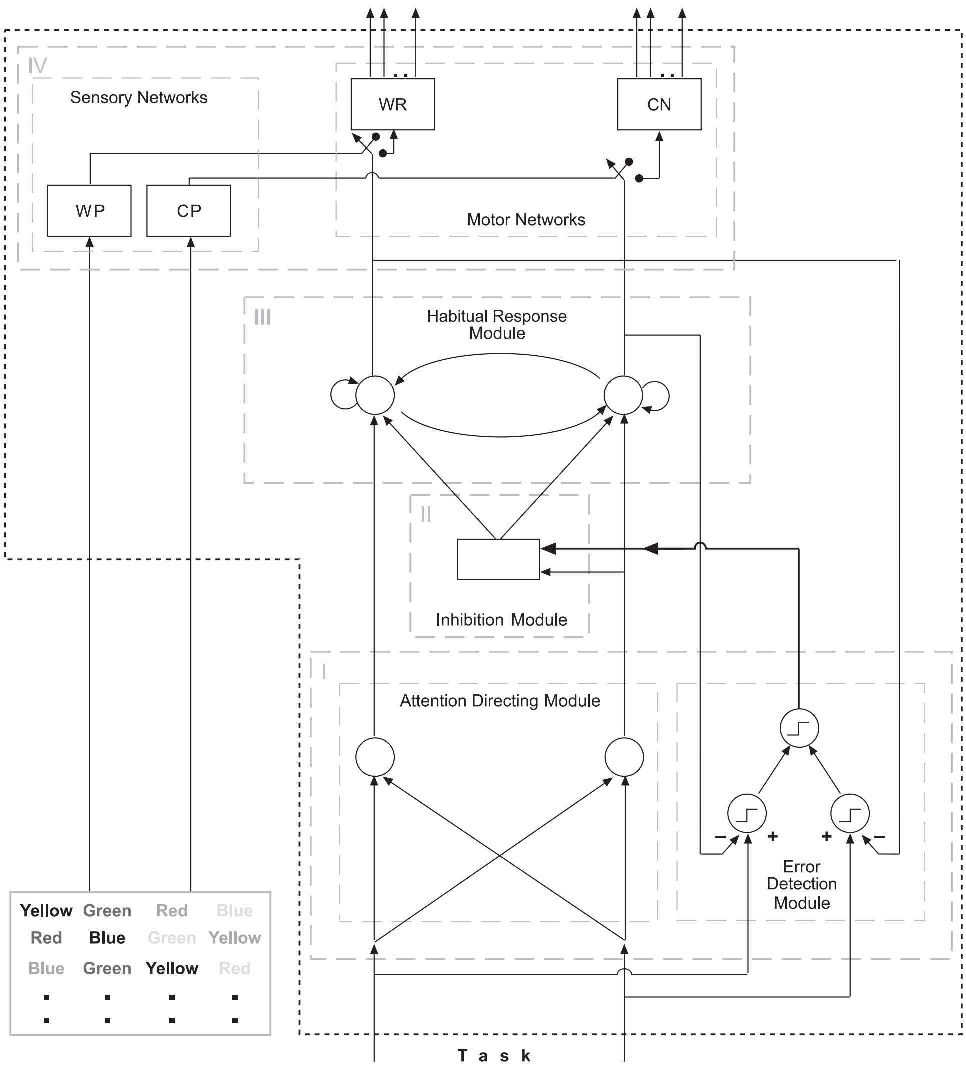

Fig. 2. The proposed connectionist model for the Stroop test. WP: word perception, CP: color perception, WR: word reading, CN: color naming. The model is composed of different ANN structures executing the functions of modules. For word reading task, once the task is stated, ANN structures corresponding to attention directing module and habitual response module take part, and in this case, from motor networks, the one corresponding to word reading completes the task. When the task is color naming, inhibition module takes turn to inhibit the tendency of habitual response module to choose the habitual behavior and conveys the selection of task-relevant action for color naming. When the habitual response module makes an erroneous choice due to insufficient inhibition from the inhibition module, error detection module checking the relevance of the decision of habitual response module with the stated task reactivates the inhibition module to provide sufficient inhibition of habitual response.

purpose. In the model, the initial condition vector of the Hopfield network varies according to the subject and also according to the inhibition efficiency. If the value of this vector is greater than certain threshold, the sum of Hopfield network outputs becomes sufficient to suppress the output of the word reading unit. The initial condition vector is generated adding different random values to the predetermined inhibition module base values in order to reach certain initial condition values. The higher the inhibition module base value, the more probable is the success of the inhibition effort. Adding random values corresponds to the modelling of the various different individual behaviors, while the different inhibition module base values correspond to the inhibition efficiency.

The habitual response module of the model, analogous to parts of BG, is proposed as a MAX-NET network with two units. The MAX-NET is a recurrent network [8] in which only the unit with the highest input value wins the competition. In the model two units compete to activate the associated sensorimotor network. The sensory and motor components of the model are two Hopfield networks; one for word reading and the other for color naming. Four color words and four different colors are encoded by four digits, accordingly the Hopfield networks are composed of four units. The weight matrices and threshold vectors are determined in such a way that the vectors of colors and color words are the stable equilibrium points of the Hopfield networks. In order to consider the influence of age and education, we preferred the continuous version of the Hopfield network and modelled this effect by step size parameter used in numerical solution of the Hopfield dynamic equations. We generated different step sizes by adding small random values to a constant step size base level.

The error detection module, analogous to the aCC in our model, takes turn when an incorrect response is generated, i.e., when an undesired prepotent response cannot be inhibited. In this case, the error detection module compares the committed action and the desired action and then generates a stimulus to reactivate the inhibition module in order to correct the error. In the model, the error detection is activated probabilistically. The error detection module generates an error signal if the produced likelihood of generating error signal parameter value is greater than a prespecified value. The error detection module is composed of three perceptrons, all with two inputs. The perceptrons at the first layer take the output vector of the BG and the task vector as inputs, and if these two values are not matching, the perceptron at the second layer generates an activation signal for the reactivation of the inhibition module.

5. Procedures for the simulation

The simulations were performed in the software environment which was developed using MATLAB. We applied the test to the model and recorded the scores like in real subjects. For the simulation purposes we considered the first and third trials. The four color words and their colors are encoded in the same manner using four binary elements. Each item is represented by concatenating its word and color vector components, so we used a binary vector of eight elements. In the model, having determined the task that will be executed, the corresponding sensorimotor network gets activated. The activated network takes the relevant part of the test item vector and generates its output. The tasks are also represented using two binary vectors of dimension two. The task and the test item vector are presented to their respective networks, i.e., the task vector is presented to the attention directing module and the test item vector to the activated sensorimotor network.

One of our major goals is to demonstrate how the components, i.e., the inhibition module, the habitual response module, the attention directing module and the error detection module, interact with each other during the performance of the Stroop task. As explained in the model, some base levels and random values were used for each component. The base levels are those parametric values which were obtained by trial-and-error approach, that were able to acquire results in accordance with the two normative studies [56,37] which had used this version of the test as noted above. In order to model the individual differences small random values are added to the base values.

The simulations were carried out using Pentium III 500 MHz computer. Since the speed of the CPU is drastically faster than the speed of biological systems, we introduced a delay process for every single processing of the components, in order to enable meaningful comparison with the human data. We imposed the delay by forcing the CPU to count a predetermined number (4000) and also some random counts (between 0 and 1000) were added in order to model the individual variations. The initial condition vector of the Hopfield network corresponding to the inhibition module is generated duplicating the value of the parameter named as the inhibition efficiency base value and the impulsive error cases are created by the likelihood of generating an error signal. Numerous simulations are carried out changing the inhibition efficiency base value from 0.4 to 0.05 and the likelihood from 0.1 to 0.9 by intervals of 0.1. As these simulation results exploit a continuous degradation in both parameters, for the likelihood parameter only two limit values are provided in Table 1.

Table 1
The simulation results of the color-naming task

Base value	Likelihood ratio	Interference time (s)	# Error	# Corrections
0.4	0.1	28.4 ± 3.2	0.4 ± 0.6	0.08 ± 0.3
0.4	0.9	28.9 ± 2.4	0.3 ± 0.5	0.08 ± 0.3
0.3	0.1	31.7 ± 1.8	2 ± 0.7	0.08 ± 0.3
0.3	0.9	33.6 ± 4	2.8 ± 1.5	0.9 ± 0.9
0.2	0.1	36.6 ± 2.2	5.6 ± 1.9	0.3 ± 0.5
0.2	0.9	39.7 ± 2	5 ± 1.3	1.75 ± 1.2
0.1	0.1	39.5 ± 2.5	9.6 ± 2.3	0.4 ± 0.6
0.1	0.9	47 ± 2.8	9.2 ± 2.7	3.3 ± 1.7
0.05	0.1	40.4 ± 2.8	11.3 ± 2.2	0.3 ± 0.7
0.05	0.9	48.3 ± 2.5	11.4 ± 1.8	3 ± 1.5

6. Simulation results

The results represent the means and standard deviations (SDs) of the simulation scores obtained for the 20 complete runs of Stroop sequences. In one complete run, depending on the task, either 24 color words are read or their colors are named. The mean time for word reading task is 11.4 ± 0.6 s (8.81 ± 1.76 s in Karakaş norms and 16.85 ± 3.34 in S&S norms). The interference scores presented in Table 1 were obtained by modifying the "base value" and the "likelihood ratio" where "base values" correspond to the inhibition efficiency and the "likelihood ratio" corresponds to the probability of generating the error signal. As can be followed through the rows of Table 1, as the base value decreases, so does the inhibition efficiency of the model which corresponds to the inhibition of task-irrelevant habitual response. This is reflected as the gradually increasing time duration of the task. When the subjects read the word instead of naming the color, an error occurs and the ability of detecting this error is reflected by the "likelihood ratio". When the value of the "likelihood ratio" is high, the number of error corrections increase and this results in the prolongation of the time to complete the task.

Through the first four rows of the base values of 0.4 and 0.3 time durations are within the normal limits of the mean minus one SD of the both Karakaş and S&S normative values (26.38 ± 12.29 and 28.9 ± 7.62 s, respectively). Starting with the base value of 0.2, time durations reach the boundary of 1SD over the mean of S&S norms (S&S mean 1SD = 36.42 s) for the 0.9 likelihood and exceed those of both of the normative values for the 0.1 likelihood (Karakaş mean 1SD = 38.7 s). Finally, the times for the two 0.1 and two 0.05 base values are clearly over 1SD for both of the normative values and accordingly indicative of abnormal performance. Higher error signal likelihood corresponding to 0.9 influences the two lower base values of 0.1 and 0.05 (rows 8 and 10) as notably increasing their time durations—compared to 0.1 likelihoods of the same base values (rows 7 and 9). This is because, when the likelihood parameter is high, the errors are more likely to be recognized by the error detection module and then the inhibition module takes part in simulations to correct the error. In such cases the number of corrections tends to be higher and the effort of correction causes the system to slow down. In this respect, "impulsive" errors of the 0.1 likelihood trials free the system from the conflict situation and makes it faster, albeit in a faulty way.

In order to see if our cut-off level of 1SD longer than the mean normative time durations is really discriminative between a normal and abnormal virtual performance on the Stroop task, we pooled the scores of first four rows (base 0.4's and 0.3's) as normal subjects and last four rows (0.1's and 0.05's) as virtual prefrontal patients, excluding the middle two rows for the base value 0.2 as they fall in the gray zone. As can be followed from Fig. 3, the bars corresponding to the base values 0.4 ($B = 0.4$) and 0.3 ($B = 0.3$) are in between 1SD of normative values of S&S and Karakaş (K). On the other hand, the base values 0.1 ($B = 0.1$) and 0.05 ($B = 0.05$) which are over the 1SD of normative values, can be interpreted as the prefrontal patients.

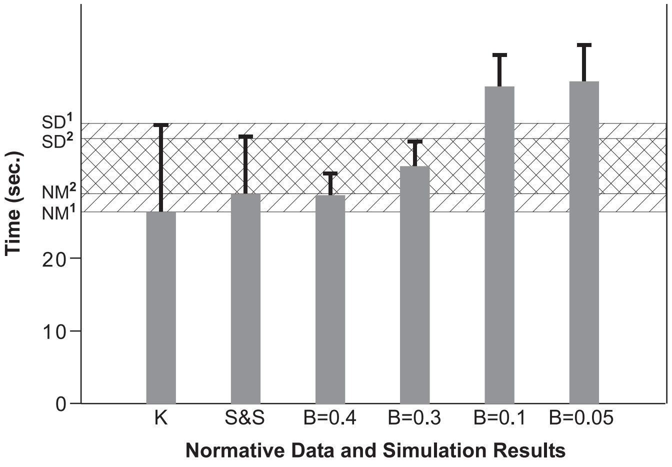

Fig. 3. Interference times in seconds for two published norms (S&S: Spreen and Strauss norms [56]; K: Karakaş norms [37]) and for four different conditions of base values ($B = 0.4$, $B = 0.3$, $B = 0.1$, $B = 0.05$). The NM^1 (26.4 s) and SD^1 (38.6 s), and NM^2 (28.9 s) and SD^2 (36.5 s) stand for normative means and +1 standard deviations of Karakaş, and Spreen and Strauss data, respectively. Left-inclined hatched area and right-inclined hatched area are the upper normal limits of S&S and K data, which is defined as the area in between the normative mean and +1SD over it. See that while the interference times for $B = 0.4$ and 0.3 stay within normal limits (28.7 and 32.7 s, respectively), those for $B = 0.1$ and 0.05 are way above this threshold (43.3 and 44.4 s, respectively), similar to prefrontal patients.

As stated above, pooling the scores of the base values corresponding to the first four rows and the last four rows of Table 1, we supposedly obtained two groups of virtual subjects: normals and prefrontals, respectively. Statistical comparison of these two groups by the *t*-test (using Graphpad Instant 3.0) showed a statistically significant difference ($p < 0.001$, $t = 15.3316$ and $df = 94$).

7. Conclusions

Ever since Stroop developed the test in 1935, there have been numerous articles on this subject [43]. To our knowledge, two of them are on connectionist models. One of them was developed by Cohen et al. in 1990 and 1998 [17,18]. Their model is a one hidden layer perceptron. The input layer consists of six nodes: two task nodes representing the task, two color nodes for red and green ink and the word nodes for words "red" and "green". The hidden layer consists of four units: two of them for the color-naming pathway and the other two for the word reading pathway. The task units activate the color-naming pathway and the word reading pathway. In order to model over-learned activity of word reading, stronger weights are assigned for the word reading pathways. The output layer consists of two nodes: one for the response red and the other for the response green. Although this model simulates the response time properly, it has been criticized for set size effects (different network size and different number of stimuli) [36]. In the same year, Phaf et al. developed the selective visual attention model SLAM (SeLective Attention Model) and they extended their model for the simulation of Stroop test [51]. The model proposes different architectures for word reading and color-naming tasks. While the input nodes for words are directly connected to the word output nodes, the input nodes for colors are connected to output nodes via hidden nodes. The model is also limited since it takes into account only response time as the performance of the Stroop test.

In addition to these two connectionist models, there is also a well-known cognitive model proposed by Norman and Shallice and it consists of two different systems, one for routine actions and the other for novel situations [55]. It was suggested that routine actions are selected by "contention scheduling" system. In contention scheduling there are competitive schemas which correspond to actions specialized in over-learned skills, and these are triggered by perceptual inputs. If a schema is activated over a threshold level, it will be selected and remain active until its goal is reached or it is inhibited by other competitive schema. This system works well, when the situation entails routine actions. When there is no selected schema or when the contention scheduling fails, it means that the situation is novel and there is a need for an additional system to deal with the novelty; hence, the "supervisory attentional system"(SAS). As stated by Shallice, the SAS has access to a representation of the environment and of the organism's intention and cognitive capacities [55]. The SAS as the general executive component acts to handle non-routine behaviors, one of which is to inhibit inappropriate schemas. The analogy to be drawn from the cognitive model of Norman and Shallice to our connectionist model can be that, while the contention scheduling schemas correspond to word reading and color-naming modules, the SAS corresponds to inhibition block shown in Fig. 1b.

Basing it on Cohen's work, Gilbert and Shallice [28] developed this cognitive model for task switching and proposed a parallel distributed processing model which simulates the Stroop effect. In the works of Cohen [17,18], Phaf [51] and Gilbert [28], only the prolonged time of interference task is considered. In Cohen and Phaf, this prolonged time is modelled in a trivial way through a time delay mechanism rather than considering the neural substrates underlying this effect.

We have not encountered a published clinical study using Victoria version other than the one which had been coauthored by one of us [31]. This was a parallel neuropsychological and ERP study investigating the cognitive profile in early amyotrophic lateral sclerosis (ALS) patients. The Victoria version of the Stroop test was also included in the neuropsychological test battery. Twenty ALS subjects were compared to age (52.9 ± 11 vs. 52 ± 12 years) and education (8.7 ± 3.7 vs. 9.7 ± 4.4 years) and matched with 13 normal control subjects. The durations of the interference task were 42 ± 22 and 29 ± 7 s, respectively, and their difference was statistically significant. The concept of ALS, as being a generalized frontal disorder, but not a pure motor disorder as previously considered, is well established now. Although a large variance of abnormal performance both in terms of time durations and number of errors and corrections can be encountered in different patient populations, this study is the only available one that we could compare with our virtual normals and patients. We think that the comparison is valid in terms of both age and education reference values and test scores.

In conclusion, we have taken into account the inhibition of task-irrelevant prepotent or habitual responses and the detection of errors committed by those inappropriate responses in our model. Modelling the behavior of normal subjects and prefrontal patients, we have used some network parameters, namely "base value" and the "likelihood ratio". While the base value determines the inhibition of task-irrelevant automated response tendency, the likelihood ratio determines the ability of detecting errors caused by inefficient inhibition.

Our perspective in modelling was not a physiological or neurobiological, but a functional neuroanatomical one. We assembled functional modules that are theoretically analogous to the neuroanatomical structures, which are presumably playing role in the particular task by ANNs. The composite model, so formed, is capable of dealing with a Stroop-like interference either quite efficiently like a normal human subject, or when some of its network parameters are changed fails the task quite like a prefrontal patient. Unlike the previous work, the task run in our model is not an approximation, but the genuine Stroop test itself that is used in the neuropsychology laboratory with the human subjects which enables direct comparisons with human data.

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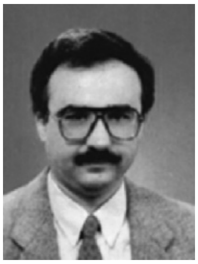

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