An electrophysiological model of working memory performance

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Golnaz Baghdadi a, Farzad Towhidkhah a,⇑, Reza Rostami b

a Department of Biomedical Engineering, Amirkabir University of Technology, Tehran, Iran
b Department of Psychology and Educational Sciences, University of Tehran, Tehran, Iran

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Abstract

Working memory (WM) enables us to keep a limited amount of information in active mode. It is believed that attention refreshes necessary information in WM and prevents their forgetting. Despite a plethora of models offered, it is not fully understood what factors may be involved in forgetfulness and in the required time for refreshing the information. In this study, an electrophysiological model of WM is proposed that consists of several resistor-capacitor units. Inspired of the “resource capacity theory,” attention as a limited source of energy refreshes the voltage level of these units. According to the “time-based resource sharing theory,” only one of these units is allowed to use the limited source of attention at each moment. The source of attention is shared between active units. This model mimics the pattern of several well-known observations of WM such as the recall interval, the word length, and the serial position effect. Some suggestions have been provided about influencing factors in WM performance. Model parameters give the ability of investigating the possible effect of some other factors on WM performance and also a probable prediction about how much information can we chunk?

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1. Introduction

Working memory is known as a system that preserves limited amount of necessary information. It has been shown that attention holds the activation of the essential information in our WM (Cowan, 1997; Oberauer, 2002; Revlin, 2012). The switching of the attention to a piece of information can refresh its activation and consequently, helps to recall it easier, so called “attention-based rehearsal” (Postle, Awh, Jonides, Smith, & D’Esposito, 2004). However, due to the limited capacity of the attention resources, we are able to keep the activity of a finite amount of information in WM (Cowan, 1997; Kahneman, 1973; Weems, Winder, Bunting, & Reggia, 2009). Based on the “time based resource sharing (TBRS)” theory proposed by Barrouillet, Bernardin, and Camos (2004), the items in WM decay over the time, unless the attention can be directed to them. In other words, when a representation of WM captures the attention, it can be refreshed and partially prevents its decay. In TBRS theory, it was assumed that only one representation of WM can use the attention at each moment of time (Barrouillet et al., 2004). These restrictions lead to several observations of WM performance such as: 1. Increasing the gap between the presentation of an item and the recalling time (i.e., delayed response) decreases the retrieval efficiency (Peterson & Peterson, 1959; Rodriguez & Paule, 2009); 2. The accuracy of recall decreases as the words length...
increases. A probable reason is that the long words have more syllables and consequently, need more time for rehearsing (Jones & Polk, 2002; Longoni, Richardson, & Aiello, 1993). However, some studies reported that the word length effect could also be observed when the rehearsal was avoided (Campoy, 2008). Hence, there would be another reason for the word length effect; 3. “Serial position effect” is one of the most attractive observations in studies of WM. That is, in remembering a list of words, the primary and endmost words of the list are retrieved with higher probability than words in the middle of the list (called “primacy” and “recency” effects, respectively). It is believed that the first word is rehearsed more than others, and the last word has shorter time to decay. Increasing the interval gap between the end of the list and the start of retrieval (with no rehearsal) decreases the “recency” effect, because the last word can find more time to decay. Increasing the rate of the items presentation reduces the “primacy” effect, because the first item finds a little or no time for rehearsing (Revlin, 2012). Despite lots of reports about the time-based decay of information, there is some strong experimental evidence that is against the timed-decay theories (Lewandowsky, Oberauer, & Brown, 2009; Oberauer & Lewandowsky, 2008, 2013, 2014). The results of these experiments indicate that interferences cause the decay of information not the passing of time. Internal or external interferences are usually received over the time. Therefore, in both cases (i.e., time-decay or interference-decay), we see the decay of information over the time.

Various computational models have been proposed to show the possible mechanisms that may lead to these results. These models provide theoretical knowledge as well as the prediction ability of the function and the performance of WM. The main differences of these models are in their process of storage and retrieval of information. Most of these models were designed according to the concept of “phonological loop,” proposed by Baddeley (1983). These models did not explicitly show the impress of attention (for a review see Lewandowsky & Farrell, 2002). Weems et al. (2009) designed an attractor neural network model to show the role of neuronal connections’ weights decay and attentional resources limitation in the WM capacity restriction (Weems et al., 2009). In 2011, a computational model of WM was also suggested by Oberauer and Lewandowsky (2011) to show the importance of attention in refreshing the information of WM. This two-layer network model was designed based on the TBRS theory in which the first and the second layers coded items and its order, respectively. Weights of connections between the first and the second layers decayed over the time and causes the decrement of the probability of the accurate recall. To compensate this decay, an attentional mechanism refreshed the weight value. Portrat and Lemaire (2015) showed that reducing the refreshing time of each item or increasing the attention span (i.e., more than one item can use attention simultaneously) could lead to fit the results of Oberauer and Lewandowsky’s model to the human data more precisely (Portrat & Lemaire, 2015). To deal with observations against the time-based decay, an extended interface-based model was presented (Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012). In this model, the interfering effect of distractors and involved parameters in the cognitive load have been introduced as factors that promote forgetting (Oberauer & Lewandowsky, 2014). The role of attention in these models is nearly the same as the “mnemonic resource” function in the visual WM model proposed by Lohmann, Herbort, and Butz (2013). In this model, visual attention contributed in the filtering of irrelevant information. Notwithstanding the various models that could approximately mimic several observations of WM performance, it is not still clear that, what biological factors may involve in the forgetfulness, the decay rate, or the required time for refreshing each item.

In this study, we present an electrophysiological based model of WM that can show some other possible factors that may influence on the information decay. In this model, each unit is the equivalent of a neuronal population. Chuderski, Andrelczyk, and Smolen (2013) proposed a promising oscillatory model that provided some predictions about the WM capacity limitation and individual differences. According to the goal of the study and to simplify the simulations, we did not consider the oscillatory units. However, the model units’ activity is actually the push or the activity sates of neuronal oscillations. The structure of the model is somehow similar to the compartmental model of short-term memory proposed by Bressloff (1993). The present model shows how attention can resolve the problem of the time-scale mentioned in the compartment model. There are some common ideas between our model, and the visual WM model proposed in Lohmann et al. (2013). Using electrophysiological concepts, we have provided possible answers to the challenges of the acceptable stimulus presentation duration and the length of the interval between the stimuli reported in Lohmann et al. (2013). The model has been evaluated based on the human data reported in the previous studies. The model provides some predictions about the possible parameters that may involve in the decay rate or the refreshing time. The probable effects of some factors such as stress and medicine consumption are also investigated.

2. Model structure

The proposed model is based on three theories and viewpoints:

1. Cowan (Cowan, 1997) and Oberauer (Oberauer, 2002) viewpoint about the WM: the focus of attention can increase the activity of an item. It is supposed that the memory of an item is represented by the activation of a resonating neuronal population. When the activity state of this population is higher than a threshold value, the item has the opportunity to be in the “direct access”
memory for further processing by the focused attention (Fig. 1). Items in the “direct access” memory can be retrieved with higher recalling probability. “Direct access” memory is considered as the limited storage part of the working memory. The term “direct access region” has been introduced in Oberauer (2009).

2. TBRS theory (Barrouillet et al., 2004): the activity state of WM items decreases over the time, and they demand the attention for refreshing their activation state. However, the changes of the involved parameters in the structure of the model can weaken or enhance the effect of the time in the forgetting. It is worth mentioning that some experiments show that information decay is not necessarily due to the time passing. It is possible that the decay is because of the interference of the previous data with new incoming information over the time (Oberauer & Lewandowsky, 2008, 2013, 2014). However, if the decay is because of the time passing or due to the interference, it seems that in both cases, attention can prevent the loss of information.

3. Attentional resource(s) theories (reviewed in Lund (2002)): in these theories, attention is considered as a (or more) restricted resource(s). In the model, we considered attention as a limited source of energy (Fig. 1). Without this source of energy (attention), the neurons’ activity state starts to decrease over the time (may be because of some internal or external interferences). The rate of this decrement can be changed by the involved models’ parameters.

As it was mentioned, in the proposed model, each unit includes a pool of neurons that their synchronous oscillations represent the memory of an item. This is the basis of the oscillatory models (Chuderski et al., 2013). Therefore, if one is requested to remember three items in a list, three units become active and start to resonate. It has been considered that the push or the activity state of each resonating unit changes by Eq. (1).

\[
V(t_2) = (V(t_1) - V_{0dc})e^{-\Delta t/RC} + V_{0dc}
\]

where \(V(t_2)\) is the activity state of an unit in time \(t_2\); \(V(t_1)\) is the activity state of the unit in time \(t_1\) (\(t_2 > t_1\), \(\Delta t = t_2 - t_1\)); \(V_{0dc}\) is the initial state of the unit’s activity (i.e., bias); and \(RC\) indicates the decay rate of the units activity state. Based on the simplified equivalent resistor capacitor (RC) electrical model of neurons’ membrane (Kandel, Schwartz, & Jessell, 2000; McTavish; Phillips, Kondev, Theriot, & Garcia, 2012), it has been supposed that \(R\) and \(C\) respectively correspond to the equivalent ion channels resistance and membranes capacitance of all neurons in the unit (see Fig. 2).

The voltage of resistor and capacitor can be calculated using Eq. (2). In this equation, \(I_R\) and \(I_C\) are respectively the resistor and capacitor current.

\[
V_C = \frac{1}{C} \int I_C \, dt
\]

\[
V_R = R \cdot I_R
\]
Fig. 3 shows the proposed electrical model of WM. Whenever an item is presented, a switch of a new RC unit is closed. This unit beside other active units would like to use the limited resources. Attention is one of the limited resources of WM that avoids data loss over the short period of time. Paying more or less attention to an item enhances or weakens its activation level, respectively. These, in turn, result in easier or harder retrieval of the item (Revlin, 2012). In our model, attention is depicted as a limited current source (I). Inspired of Oberauer viewpoint (Oberauer, 2002), and TBRS theory (Barrouillet et al., 2004), only one item can be under the focus of attention. Therefore, we assume that just one RC unit can use the current source in each moment. There is no need to refresh an RC unit, if its activity is greater than a threshold value. Thus, the current source (attention) can be switched to another item that needs refreshing. The switches of RC units are opened or closed in the following situations:

Switch is CLOSE when:
1.  
   \((j)^{th} \text{RCunit}(i = j)\) is attached to the system \((j)^{th} \text{item is presented}) for the first time.
2.  During the interval gap of two successive representations, the voltage of the \((j-1)^{th} \text{RCunit}(i = j)\) be lower than the threshold value.

Switch is OPEN when:
1.  
   \((j)^{th} \text{RCunit}(i \neq j)\) is attached to the system \((j)^{th} \text{item is presented})
2.  During the interval gap of two successive representations, the voltage of the \((j-1)^{th} \text{RCunit}(i = j)\) be higher than the threshold value and there are more than one RC unit (item) in the system that all want to use the current source for refreshing.

In Fig. 3, five items are allowed to be remembered. However, this model can be easily extended for more items.

Suppose that a subject is requested to remember different items for a short period of time. These items are represented as the activation of the neurons populations. However, without the focusing of attention on these items, neurons gradually lose their activations. Consequently, items are being forgotten and exited from the “direct access” memory. It is assumed that each item can remain in the “direct access” memory if the activation of its related neurons be higher than a threshold value. Attention refreshes neurons activations and restores their reduced charges. This is like the “strength concept” used in the visual WM (Lohmann et al., 2013). Eq. (1) shows the charging formula of a capacitor based on its current. The voltage of the capacitor starts to discharge (by Eq. (1)), as soon as detaching from the current source (attention).

When the order of items in the list becomes important, or if it is tried to remember items orderly, it can be assumed that each RC unit has a relationship with its pre and post units. Using this relation, activation of a unit can cause the activation of its next neighbor unit in the stage of retrieving. Consequently, items (units) can be recalled orderly. When this relation becomes weak, recalling in the correct order becomes harder. This relationship is modeled by a nonlinear variable joint resistor that couples two units to each other \((r_{i,j})\) in Fig. 3. The value of the variable resistor, \(r_{i,j}\), is infinite when \(j\)th RC unit (\(j\)th RC unit) is presented after \(i\)th item for the first time \((j = i + 1)\). Therefore, at first, two successive units are completely independent of each other. The value of this resistor decreases whenever \(i\)th item is refreshed after \(i\)th item \((j = i + 1)\). When the value of this resistor is large, its voltage drop is greater. The more repetition of the mentioned procedure leads to more decrease of \(r_{i,j}\) and consequently, increases the coupling between two successive units. However, this joint resistor is activated by a delay. The delay was equal to the required time for recharging the pre and post units to a value higher than the \(V_{th}\). Eq. (3) shows the changes of the variable joint resistor in different situations.

\[
\begin{align*}
   r_{i,j} &= \frac{1}{RR_{i,j}} \\
   RR_{i,j} &= (RR_{i,j} + 1)u(t-d) \quad \text{whenever the current source switches from item } i \text{ to } j (j=i+1) \\
   RR_{i,j} &= 0, \quad \text{otherwise} \\
   u(t-d) &= \begin{cases} 
   1 & t \geq d \\
   \infty & t < d
   \end{cases}
\end{align*}
\]

In Eq. (3), \(t\) is the current time and \(d\) is the required time for recharging the \(j\)th RC unit \((j = i + 1)\). Once a new item is presented, it captures all the attention source during the presentation duration. As there is no rehearsing or refreshing during the presentation duration (Peterson & Peterson, 1959), previous presented units (items) would be detached from the current source through this period of time. In other words, based on TBRS theory, new item cannot share the presentation duration (if it is not long) with previous items to use the attention source. In the inter stimulus interval (ISI), all previous active units find the opportunity to use the current source (attention) to refresh and compensate their reduced activities. However, each unit can use
3. Model simulation and results

This section is divided into two parts. The first part (model validation) consists of the procedure and results of the simulation of three famous scenarios to evaluate the performance of the proposed model. In the second part (model prediction), a possible prediction of the size of chunking is presented. In simulations of these two parts, the following assumptions have been considered.

3.1. Simulations assumptions

1. The entrance of an item into the “direct access” memory is represented by adding an RC unit into the model.
2. Each item (represented by the activation of an RC unit) can enter and stay in the “direct access” memory, if the activation of its capacitor ($V_C$) is higher than a threshold. Previous study showed that at least 0.5 s require finishing this procedure. Therefore, we set the time duration of the presentation of an item to 0.5 s. The activity level of the corresponding capacitor meets the threshold during this time interval.
3. According to results of previous studies, it can be claimed that the rehearsal or refreshing procedure is done in the time interval between two successive items and not during the presentation of a new item (Peterson & Peterson, 1959). Once a new item is presented, it captures the attention source and uses the full amount of resources to charge its related equivalent capacitor. Therefore, no energy remains for the previous items (RC units) to be refreshed. That is, their switches (see Fig. 3) are opened.
4. In the time interval between two successive items, if the rehearsal mechanism is allowed, RC units (items) can attach to the current source (attention) to be refreshed and compensate their reduced level of activation. However, the connection of the previous active RC units to the current source can be done by the following mechanism:
   a. Items (RC units) are connected to the source one by one, orderly. When an item is refreshed (i.e., its voltage level becomes higher than the threshold, $V_{th}$), it is disconnected and replaced by the next item. Therefore, at each moment just one item uses the attention source ($I$ in Fig. 3).
5. Items in the “direct access” memory (i.e., RC units with $V_C > V_{th}$) are recalled with higher level of probability. Decreasing the value of $V_C$ leads to the reduction of the probability of recall. Eq. (4) shows the relation between the voltage level of the capacitor in an RC unit and the probability of recall.

$$\text{probability of accurate recall} = \begin{cases} 1 & V_C > V_{th} \\ \frac{V_C}{V_{th}} & V_C < V_{th} \end{cases}$$

(4)

3.2. Model validation

In order to validate the proposed model, the following scenarios that are among the most important issues in WM studies are simulated.

1. Effect of the recall interval on the probability of retrieval
2. Effect of the word length on the probability of recall
3. Effect of serial position
The results were evaluated based on the previous reported human data. These scenarios and their simulations results were explained in more details as follows.

3.2.1. Effect of the recall interval increasing on the probability of recall
3.2.1.1. Scenario of the experiment. An (auditory or visual) item was presented to the subject for a short period of time (presentation duration). The subject was requested to retrieve that item as soon as receiving a recalling signal. Then, the experimenter waited for the response of the subject (recall the item). The time duration between the end of the item presentation and the appearance of recalling signal was named “recall interval” (see Fig. 4). In order to avoid refreshing of the item, the subject was demanded to count backward a three-digit number during the recall interval. In other words, backward counting process did not share the time with the process of remembering items. The time interval between receiving the signal of recall and the response of the subject was called “latency” of response (Peterson & Peterson, 1959).

3.2.1.2. Model simulation. Considering Fig. 3, once an item was presented, one of switches (i.e., switch 1) was closed, and its RC unit used the current source. The capacitor was presented, one of switches (i.e., switch 2) was opened to avoid refreshing the voltage level of the capacitor at the end of the presentation duration. The probability of recall was calculated and the simulation of the electrical model of WM to show the effect of the recall interval on the probability of recall. Column 2 and 3 were calculated based on Eqs. (2) and (4). The simulation of the electrical model of WM to show the effect of the recall interval on the probability of recall. Column 2 and 3 were calculated based on Eqs. (2) and (4). The simulation of the electrical model of WM to show the effect of the recall interval on the probability of recall. Column 2 and 3 were calculated based on Eqs. (2) and (4). 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It is observed that despite the changes in the parameters value, the pattern of the results has been preserved. Comparing the solid line with filled square marks and dashed line with multiplication marks shows that reducing the amplitude of the current source ($I$) changes the position of the graph in the zero point. Considering the solid line with filled square marks and the lines with triangle and hollow square marks indicates that increasing the ion channels resistance ($R$) decreases the forgetting rate (i.e., the slope of the diagram) and has no effect on the intersection point with the $y$ axis. A comparison between the solid line with filled square marks and the point line with hollow circle marks shows that increasing the value of the membranes capacitance ($C$) affects on the forgetting rate and the position of the graph in the zero point. However, decreasing the $C$ value, which has been shown by the line with cross marks, has just led to a change in the forgetting rate. Comparing the solid line with filled square marks and the dashed line with filled diamond marks demonstrates that changing the initial constant potential ($V_{0dc}$) changes the forgetting rate.

3.2.2. Effect of the word length on the probability of recall

3.2.2.1. Scenario of the experiment. In this experiment, different lists of short and long length words (based on the number of syllables) were presented to the subjects. At the end of each list, they were requested to recall items orderly. It was observed that subjects recalled the list of short length words with higher probability than the long length words, with (Longoni et al., 1993) and without (Campoy, 2008) the permission of the rehearsal. The performance of memory in recalling a long length word, is commonly attributed to the requirement of more time for rehearsing these words (Longoni et al., 1993). However, the effect of word length has been also observed in the absence of rehearsal mechanism (Campoy, 2008). Therefore, there may be another factor behind this effect. Brain imaging studies have shown that neural activity in long length words processing is higher than that of short length words (Baciu et al., 2002). According to this observation, length of the words can be related to the conductance and activity of neuronal units.

3.2.2.2. Model simulation. Considering the above explanation, higher conductance of neurons can be corresponded with the $y$ axis. A comparison between the solid line with filled square marks and the point line with hollow circle marks shows that increasing the value of the membranes capacitance ($C$) affects on the forgetting rate and the position of the graph in the zero point. However, decreasing the $C$ value, which has been shown by the line with cross marks, has just led to a change in the forgetting rate. Comparing the solid line with filled square marks and the dashed line with filled diamond marks demonstrates that changing the initial constant potential ($V_{0dc}$) changes the forgetting rate.

Fig. 5. The effect of the length of the recall interval on the probability of recall; Dashed line shows previously reported data from humans [Source: (Peterson & Peterson, 1959)]; Solid line is the simulation results of the proposed electrical model for WM. These values have been used for the simulation: $C = 50 \text{ mF}$, $I = 5 \text{ A}$, $R = 100 \text{ \Omega}$, $V_{0dc} = 70 \text{ mV}$, $V_{th} = 45 \text{ V}$.

Fig. 6. The effect of changing the recall interval on the probability of the recall in the proposed model. This effect has been investigated with different values of parameters. The results of simulation with different ion channels resistances ($R = 50$, 100, and $200 \text{ \Omega}$) has been shown by lines with hollow square, filled square and triangle marks. The effect of changing the membranes capacitance ($C = 10$, 50, and 100 mF) has been demonstrated by lines with cross, filled square and hollow square marks. The result of changing the initial constant potential ($V_{0dc} = 0.5$ and 70 mV) has been shown by lines with filled diamond and filled square marks. The simulation result for different values of the current source amplitude ($I = 3$ and 5 A) has been demonstrated by lines with multiplication and filled square marks. The slope of the diagram (i.e., forgetting rate) and the position of the intersection point with the $y$ axis have changed in different simulations. The values of parameters in each simulation have been demonstrated on the right side of the figure.
to the opening of more ion channels and consequently, lower amount of $R$ in the model. Thus, the $R$ values were chosen high, for short length words, and low, for long length words, respectively. This simulation was performed for remembering words with different lengths. As mentioned, length of the word has been represented by the value of $R$ in simulations. It is assumed that the word has been presented for 0.5 s, refreshing was avoided, and the recalling stage started 2 s after the end of presentation.

Eq. (6) shows the mathematical procedure of the simulation for a word with a certain length ($R = 1000 \Omega$). The threshold voltage was set to 45 V. A same procedure was repeated for different lengths ($R = 800, 600, 400, 200, 100$, and $50$), which its results has been represented in Fig. 7.

\[(\text{identification of the item}) \Rightarrow V_C = [(V_{C0} - RI + V) e^{-\pi + RI - V_{th}}]_{I_{peak}} \]
\[R = 1000 \Omega \]
\[\Rightarrow V_C = \left[(-100 \times 5 + 70 \times 10^{-3})e^{\frac{45 - 100}{45}} + 100 \times 5 - 70 \times 10^{-3}\right]^{0.5} = 47.57V \]

The result shows that the probability of recall for shorter words (i.e., higher values of $R$) is higher than that of for longer words (i.e., lower values of $R$). Comparing the square marked line with the circle marked line shows that decreasing the value of $C$ affects on the recalling of words with high length. The line with triangle marks in comparison with the square marked line indicates that the more increment of the $C$ value causes a considerable drop in the probability of recall in all word lengths. A same result has been observed in reducing the current value ($I$), which is shown by the line with star marks in Fig. 7. The dashed line with multiplication marks and the square marked line are almost identical. Therefore, the initial constant potential ($V_{th}$) has no effect on the recalling probability of words with different lengths in the proposed model.

3.2.3. Effect of serial position

3.2.3.1. Scenario of the experiment. As mentioned in the introduction, “serial position effect,” is one of the most famous and challenging observations of WM performance tests that has captured the attention of scientists for many years (Botvinick & Plaut, 2006; Howieson et al., 2011; Revlin, 2012). In this scenario, lists of items (visual or auditory) were presented to the subjects. They were requested to recall items orderly. Regardless of the length of the list and the type of the items, it was observed that the probability of recall for items in the first, and the end of the list is higher than items in the middle. In other words, the probability of recall depended upon the position of an item in the list.

3.2.3.2 Model simulation. We considered the scenario of presenting a list of five items to the subject. Each item has been presented for 0.5 s with the ISI of 1.5 s. Two seconds after the presentation of the last item, the subject requested to recall items orderly (see Fig. 8). Table 2 shows the process of charging and discharging of the capacitor of all five units during the experiment. The scenario presented in Table 2, is approximately similar to the on-line and off-line consolidation processes introduced in Lohmann et al. (2013). That is, on-line consolidation of the item occurs in the presentation duration, and off-line consolidation happens in the ISI.

As shown in Table 2, once a new item is presented for few seconds (i.e., presentation duration), the capacitor in its correspondence RC unit captures the current source
(attention) for charging to the threshold level. This phase corresponds to the presentation of the new incoming item. During this time, the capacitor of all other RC units (if existed) cannot use the current source for refreshing. Therefore, their activation level gradually starts to decrease resulted in forgetting the items. During ISI, the active capacitors find the chance of taking the current source orderly for compensating their reduced activity. However, if the number of items is high, last items may have no enough time for refreshing. According to Eq. (3), the more re-attending (recharging) of two successive items can lead to the more increase in their coupling (reducing $r_{ij}$). This increases the probability of successful recall of these two items orderly. Fig. 9(a) shows the charging and discharging of the 5 capacitors during the experiment. Based on the voltage value of each capacitor at the end of the simulation, the probability of accurate recall for each item was calculated (using Eq. (4)) that is shown in Fig. 9 (b). The values of joint resistors ($r_{ij}$) are shown in Fig. 9(c). In this simulation, rehearsal was allowed during recalling interval. In Fig. 9(a), the first capacitor (item) charged more than others because in the first gap, there is no item before and after it.

Fig. 9(a) shows that capacitors C1, C5, C4, C3, and C2 respectively have the higher amount of voltage at the end of the simulation (recalling stage). Based on these voltage levels, items in the 1st, 5th, 4th, 3rd, and 2nd positions have orderly the highest amount of the probability of accurate recall (see Fig. 9(b)). Fig. 9(c) shows that the coupling $(1/r_{ij})$ of items 2 and 1 is higher than that of items 2 and 3 and so on to the next items.

The above simulation was repeated for higher rate of the presentation of items (ISI = 0.01 s and recall interval = 0.05 s) and longer period of recalling interval (ISI = 1.5 s and recall interval = 8 s) with and without rehearsal permission during this interval. Fig. 10 shows the results.

In Fig. 10, the comparison between solid lines with circle and multiplication marks indicates that decreasing the time interval between two successive presentations (ISI) caused the reduction of the recalling probability of the first item. Comparing the triangle and square lines shows that avoiding the rehearsal caused the decrease of the probability of recall of all items, especially the last one (with no rehearsing).

In previous simulations that their results were shown in Figs. 9 and 10, the value of the model parameters (such as
the ion channels' resistance, the membranes' capacitance, the initial constant potential, and the current source amplitude) were equal to values that led to a good fitting between the model output and the recorded data from the human shown in Fig. 5. In order to investigate the sensitivity of the model to the value of these parameters, several simulations were done by changing the ion channels' resistance ($R = 50, 100, \text{ and } 200\Omega$), the membranes' capacitance ($C = 10, 50, \text{ and } 100 \text{ mF}$), the initial constant potential ($V_{0dc} = 0.5 \text{ and } 70 \text{ mV}$), the current source amplitude ($I = 3 \text{ and } 5 \text{ A}$), and the presentation duration ($pd = 0.3, 0.5, \text{ and } 0.7 \text{ s}$). Fig. 11 shows the results of these simulations.

Comparing the results demonstrated in Figs. 10 and 11 reveals that a large increase of the membrane capacitance (shown by a dotted line with filled triangle marks in Fig. 11), the reduction of the presentation duration (shown by a solid line with circle marks in Fig. 11), and the decre-

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**Fig. 9.** The result of the model simulation for the position effect: the result of the model simulation; Five items (visual or auditory) are orderly presented and requested to be remembered. The item in the 1st position presented first and so on for other items (serial position). (a) The charging and discharging of the five capacitors (i.e., items) during the experiment. The charge and discharge times are respectively considered as remembering and forgetting the items in the model. Each capacitor (i.e., equivalent membrane capacitances of a population of neurons) is assigned to store one item. The higher voltage level of a capacitor ($V_{ci}, i = 1, 2, \ldots, \text{ and } 5$) represents the higher probability of recall in a certain time; (b) The effect of serial position on the probability of recall. According to the panel (a), the voltage level of the first and the last capacitors (i.e., the first and the last items) are higher than the $V_{in}$ at the end of the simulation. Consequently, the first and the last item can be recalled with the probability equals to one. As the same way, other items in the fourth, third, and second positions respectively have the higher level of recall probability; (c) the value of joint resistors ($r_{ij}, i = 1, \ldots, 5, j = 2, \ldots, 5$) at the end of the simulation; Joint resistors a couple of two RC units to each other. It is most likely the fifth item can be recalled after the fourth item (i.e., $r_{4-5}$ has the highest value). These values have been used for the simulation: $V_{Cin} = 0, C = 50 \text{ mF}, I = 5 \text{ A}, R = 100 \Omega, V_{0dc} = 70 \text{ mV}, V_{in} = 45 \text{ V}, \text{ ISI} = 1.5 \text{ s}, \text{ recall interval} = 0.05 \text{ s}; \text{ presentation duration} = 0.5 \text{ s}.
chunking procedure is usually used to increase the memory span or to facilitate the remembering procedure. In summary, this strategy helps to use the limited capacity of WM more efficiently. The chunking of information cannot be continued to infinity. It is not exactly known that to what extent one can chunk pieces of information. In other words, it has not been mentioned that why we cannot chunk infinite amounts of information together? Is there any physiological reason behind this limitation? The model was applied to present a possible reason to explain what may limit us in chunking information, or what possible effective factors in the working memory span are? The simulation procedure in this regard is as follows.

3.3. Model prediction

Grouping several items together and making a piece of information was called “chunking (Miller, 1956).” The

chunking procedure is usually used to increase the memory span or to facilitate the remembering procedure. In summary, this strategy helps to use the limited capacity of WM more efficient. The chunking of information cannot be continued to infinity. It is not exactly known that to what extent one can chunk pieces of information. In other words, it has not been mentioned that why we cannot chunk infinite amounts of information together? Is there any physiological reason behind this limitation? The model was applied to present a possible reason to explain what may limit us in chunking information, or what possible effective factors in the working memory span are? The simulation procedure in this regard is as follows.

3.3.1. Chunking information

In the model simulation, chunking two or more items are considered as a connection of two or more RC units together ($r_{ij} = 0$). Fig. 11 shows the changes of RC units’ voltage value when every two second a new item is chunked with its previous items.

According to Fig. 12, chunking more items together has led to the reduction of the activation of RC units. For example, suppose a subject requested to remember three digits “6”, “8”, and “9” and recall them orderly. He may chunk and encode them into his memory as one number “689” (i.e., six hundred and eighty-nine). If the presented numbers are increased to five digits, “6”, “8”, “9”, “5”, and “4”, chunking them as “68,954” (i.e., sixty-eight thousand and nine hundred and fifty-four) led to the reduction of the activation of RC units in comparison with the previous scenario (i.e., three digits). After chunking ten items (e.g., “6”, “8”, “9”, “5”, “4”, and “3”), the voltage of the RC units has reduced below the threshold value. Therefore, based on the considered parameters value (i.e., $C = 50 \text{ mF}$, $I = 5 \text{ A}$, $R = 100 \Omega$, $V_{th} = 70 \text{ mV}$, $V_{th} = 45 \text{ V}$), only ten items can be chunked. When the level of current source (attention) increases from 5A to 6A, more items (i.e., 10–13) can be chunked with acceptable activation (higher than $V_{th}$). The increment of $R$ value from 100 $\Omega$ to 120 $\Omega$ also leads to the increase of chunking capacity (i.e., 10–16).

4. Discussion

In this paper, a new electrical-based model was presented in which attention was considered as a limited source of energy. This source has a key role in the performance of WM that is in agreement with the Cowan and Oberauer (Cowan, 1997; Oberauer, 2002) findings. The elements of the model are the equivalent electrical circuit of a population of neurons that keeping their persistent activity shapes WM. However, changing the coupling resistors $r_{ij}$ (Eq. (3)) can be considered as the synaptic plasticity that has been considered as an alternative mechanism in shaping WM (Sandberg, Tegner, & Lansner, 2003).

The effect of increasing recall interval is one of the main concerns of studies on the delayed response task
The results of model simulations showed that increasing the recalling interval led to the less accuracy of retrieval (See Fig. 5), which is consistent with the reported results of previous studies (Peterson & Peterson, 1959; Rodriguez & Paule, 2009). According to Fig. 5, the highest probability of recall is for the point that the graph crosses the vertical axis. It has been believed that the position of this point on vertical axis correlates with the individual attention to the task (Rodriguez & Paule, 2009). Our model confirms this notion, since decreasing the amplitude of the current source (attention) reduces the accuracy of recall in this point (Fig. 6). Hence, this point is suggested as an index for estimating or quantifying individuals’ attention level. Increasing the value of $C$ also led to the reduction of the forgetting rate and the recalling probability in the mentioned point.

Changing the ion channels permeability ($R$), or the initial constant potential ($V_{dc}$) has no effect on the position of this intersection point. Therefore, stimulants that can increase the membrane capacitance may shift the intersection point and consequently, the individuals’ attention level.

Changing the values of $R$, $C$ or $V_{dc}$ can influence on the rate of forgetting (Fig. 6). The forgetting rate increases after ischemic, radio-frequency, or bilateral ibotenate lesions of the hippocampus (Zola et al., 2000). These kinds of lesions activate ion channels (Huang, Delikanli, Zeng, Ferkey, & Pralle, 2010; Krosggaard-Larsen, Honore, Hansen, Curtis, & Lodge, 1980; Weilinger et al., 2013) that can be modeled by decreasing $R$ in the simulations. Fig. 6 shows that the reduction of $R$ value leads to the increment of the forgetting rate. This result reinforces the reported effect of these lesions on forgetting rate and suggests the changing of ion channel permeability as a possible reason for this observation.

Cathodal transcranial direct current stimulation, which causes a hyperpolarization of the resting membrane potential ($V_{dc}$) (Nitsche & Paulus, 2000), can enhance the WM performance (Carvalho et al., 2015; Heinen et al., 2016). This result is in agreement with the outcomes of the model simulation in which the reduction of the $V_{dc}$ value causes the decrement of the forgetting rate (Fig. 6).

In results shown in Fig. 6, it was demonstrated that decreasing the value of the membrane capacitance ($C$) led to the increase of the forgetting rate. It seems that this result is inconsistent with the enhancement of the recalling probability of middle items by decreasing the membrane capacitance ($C$) (shown by a solid line with filled square marks in Fig. 11). However, it should be mentioned that the scenario of the serial position effect has been simulated with a constant inter stimuli interval equals to two seconds, and results demonstrated in Fig. 6 are for different recalling intervals. Therefore, changing the inter stimuli interval may
affect on the pattern of results observed by the decrement of the membrane capacitance in the serial position effect.

The outcomes of the model simulations for the “serial position effect” show that time is another important factor that besides other variables can influence on the performance of WM. Fig. 9(a and b) that exhibits the “serial position effect” is consistent with the previous reported U-shaped human data (Revenson, 2012). According to this figure, the corresponding capacitor of the first item has more time to charge, and the last item has little time to discharge. Accordingly, at the end of the list, the first and the last capacitors (items) have a higher activation level with respect to the middle ones. Based on the concept of “activity-based memory” (Smith & Kosslyn, 2007), greater level of activation can be related to the higher probability of recall. Decreasing the presentation duration and increasing the recall interval are factors that can change the U-shaped plot (Fig. 10). Fig. 9(c) shows that traveling from the first item to the last, the coupling of two successive items decreases. Because, the first successive items have more time to be repeated in tandem. The repetition enhances the connection between two successive items. Last items cannot find enough time to be repeated successively that leads to the lower coupling (higher resistor value). When the coupling of two successive items increases (or their joint resistor value decreases), the amount of voltage drops on their joint resistors decreases. Hence, the activation of the first item can easily activate the second one in the retrieval phase. Joint resistors have used to present the order of items. That is, if these resistors are small enough, the activation of one item can facilitate the activation of its neighbor item and so on to the end of the list. Increasing the number of items leads to the less successive repetition of last items. Thus, in last items, when the (i − 1)th item activates most of its activation drops on the joint resistor and cannot help to facilitate the activation of ith items.

Compared to the previous models (reviewed in Lewandowsky and Farrell (2002)) that explain the “serial position effect,” our model has the advantage of providing a relation between the model parameters and some biological factors. It helps us to offer predictions about the possible biological reasons involved in producing different effects.

The model has four important variables, $R$, $C$, $V_{\text{dec}}$, and $I$, which lend themselves to investigate the effect of some brain problems that disturb the electrical properties of neurons. For example, in the trauma brain injury (TBI), ion channels are impaired (Johansson & Rönnbäck, 2014). This defect can be modeled by the change of the resistor value ($R$) to demonstrate the WM performance variation. Abnormal stress is another mental disturbance that causes the impairment of WM. Stress increases the permeability of some ion channels (Karwowski, 2001). Therefore, the effect of stress can be imposed by changing the value of $R$ in the model. The greater amount of stress (i.e., lower value of $R$) may lead to the lower probability of recall and vice versa (Luetthi, Meier, & Sandi, 2008; Schoofs, Preuß, & Wolf, 2008), which is consistent with our results demonstrated in Fig. 11. Treatment interferences such as some drugs or medicines, usually target the ion channels (Kaczorowski, McManus, Priest, & García, 2008). Therefore, the value of resistors in the model can be mutated to show the positive or negative effects of some external interference. Medicines that open more ion channels, can be simulated by decreasing the $R$ value and vice versa. Using these interferences, we have the ability to manipulate the rate of the information decay in WM and consequently, changing the accuracy of recall. For example, if we want to keep the short-term memory for longer time, inhibitory medicine such as Carbamazepine or Levetiracetam is suggested. They decrease the opening of some ion channels (Lee, Chen, & Liou, 2009; Yoshimura et al., 1995), increase the resistor value and reduce the speed of discharging. The improving effect of these medicines on WM performance was reported in previous studies (Eddy, Rickards, & Cavanna, 2011). Consequently, the proposed model demonstrates its ability to use to forecast the possible effects of changes in the level of stress or the consumption of some special medicines on the WM performance. In the simulations, a fixed value was considered for the variables. However, individual differences can be entered into the model 1. by adding a limited amount of uncertainty to these fixed values; 2. by using the predictive parameter or the “focus of attention capacity,” respectively introduced in Lovett, Daily, and Reder (2000) and Chuderski, Stettner, and Orzechowski (2007); 3. extending its structure using the idea proposed in the oscillatory model of the Chuderski et al. (2013).

Increasing the length of the words is another factor that reduces the recalling probability (Campoy, 2008; Longoni et al., 1993). Processing of long length words increases the neural activities (Baciu et al., 2002). Accordingly, the value of $R$ in memorizing long length words has been
considered lower than that of short length words in the simulations. Using this consideration, the results of simulations are consistent with the reported human data (Fig. 7). Based on the electrical rule of the capacitor, decreasing the \( R \) value in a circuit reduces the speed of charging and discharging. The reduction of charging speed in the simulations conforms to the reported decrement of the long length words reading rate in human data (Baddeley, Thomson, & Buchanan, 1975). However, the observed decline of the recalling probability of long length words may not be due to the low rehearsing rate. Because, this decline can also be observed when the rehearsing is suppressed (Campoy, 2008). Hence, the decrease of long length words reading rate may lead to the incomplete charging of neuronal units that preserve each word. That is, long length words need more time to encode correctly than that of short length words. The model predicts that setting the duration of the words presentation with respect to their speech rates may attenuate the effect of word length.

According to the previous discussion, it can be claimed that in addition of medicines, some physical features of the sensory stimuli (e.g., length of the words) can affect on the fast or slow decay of the neuron activity. That is, each feature of a stimulation that can increase the opening of ion channels (decreases the value of \( R \)), leads to the lower performance of WM. Therefore, the consequences of the inhibitory interference (increasing \( R \)) to compensate the negative effect of the long length words (decreasing \( R \)) would be worth to be investigated. The structure of the model suggests that the alternation of \( C \) (membrane capacity), \( I \) (current source amplitude), and \( V_{0dc} \) (initial constant potential) values can change the word length effect. However, the pattern of the results is preserved as shown in Fig. 7. Decreasing the membrane capacitance \( (C) \) increases the recalling probability in all word lengths. Changing the initial constant potential had no effect on the pattern or the quantity of results. These results are in agreement with that of observed in the serial position effect (Fig. 11). It can be proposed that the usage of stimulants that can increase the membrane capacity may have negative effect on the recalling probability of all word lengths. In contrast, stimulants that cause a large decrement of the membrane capacity may just affect on the recalling probability of words with large length.

The model also presents a possible justification to show to what extend the information can be chunked. Chunking more information helps us to use the limited capacity of WM more efficiently. Empirically, it can be observed that chunking has its own limitation. In other words, it is impossible to chunk infinite pieces of information together. However, the factors which impose this restriction have not been known yet. Chunking different items are as a result of strong connection between the memory units that each of them preserves one of these items (Cowan, 2012). In the model, it was represented by setting the joint resistors to zero. The model simulations demonstrate the limitation in the size of chunking (Fig. 12). The results suggest that two parameters may lead to this limitation: 1. level of attention, 2. permeability of ion channels. Increasing the attention and decreasing the ion channels resistance can lead to chunk more items.

In summary, two main results can be concluded from the model simulations: 1. “The brain cannot be full (Cowan, 2012),” and the limitations of WM may relate to the attention resource capacity, electrical properties of neurons (permeability of ion channels, the membrane capacity, and initial constant potential) and the time. Previous studies attributed the WM capacity restriction to the capability of attention (Cowan, 2012), to the interaction between attention and some cognitive processing resources (Fougnie & Marois, 2006), and to the trade-off between the number of items and the ability to distinguish them (Chuderski et al., 2013); 2. The accepted strong linkage between WM and attention is confirmed (Kiyonaga & Egner, 2013) and the proposed model, in the current level of development, suggests that this connection is required in the stage of transferring information from long-term memory into the “direct access” memory (encoding), and to avoid this transferred information to forget (maintenance), that are in line with the outcomes of previous experimental researches (Fougnie, 2009); 3. It can be suggested that the sufficiency of the exposure time or the ISI, which has been challenged in Lohmann et al. (2013), may depend on the electrophysiological characteristics of neuronal populations that represent the content of WM.

5. Conclusion

In this study, using the equivalent electrical model of neurons’ membrane, attention-based view point of WM, resource capacity theory, and TBRS theory, a new electrical-based model of WM was presented. The model evaluated using the previous reported human data. Effect of word length, recall interval and serial position were evaluated using the previous reported human data. Effect of word length, recall interval and serial position were shown by the model, and a prediction about the possible reason of chunking limitation was offered. In addition, the suggested model has the ability to show the influence of some factors on WM performance.

For future works, the extension of the model to show the individual differences and to simulate the abilities of disturbance rejection, selective updating, and the effect of similarity between items is suggested.

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