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Executive control of retrieval in noun and verb generation

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Abstract

In verb/noun generation experiments, participants have to produce a word associated with a stimulus (usually a noun) and belonging to a given syntactic category ("verb" or "noun"). The explanation of RT performance in the verb generation task is partial and debated, with different proposals emphasizing either associative strength or competition among task-relevant responses. This paper presents a novel account of RT performance in noun and verb generation, which relies on the functional interaction between associative retrieval and executive control and takes explicitly into account the interference from task-irrelevant responses. We hypothesize that fundamental control processes in this generation task are the strategic allocation of attention on retrieval cues and post-retrieval response checking and response inhibition. An analytic model based on this account accurately reproduced the major empirical trends observed in three populations (young adults, older adults, Parkinson's disease patients). The contribution of the proposal for the explanation of noun and verb generation performance, its limitations, and more general implications for other generation tasks and computational theories of retrieval are discussed.

Keywords: Executive control; Verb generation; Associative retrieval; Generation task; Inhibition

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1. Introduction

Several studies have investigated cognitive processes underlying generation tasks, including letter fluency, category fluency, option generation, and noun/verb generation (e.g., Crescentini, Mondolo, Biasutti, & Shallice, 2008; Del Missier & Terpini, 2009; Rende, Ramsberger, & Miyake, 2002). In particular, in the domain of language production, word generation tasks have often been used to investigate control processes involved in semantic/syntactic generation and response selection/competition (Martin & Cheng, 2006; Persson et al., 2004; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997; Thompson-Schill, Kan, & Oliver, 2006). Despite these research efforts, the debate on the cognitive mechanisms underlying semantic/syntactic generation and on the functional and anatomical organization of processing in task-related brain regions is still vivid and unsettled.

The most frequently used experimental paradigm in this stream of studies is certainly the verb generation task. In noun/verb generation experiments, participants have to produce a word associated with a stimulus (usually a noun) *and* belonging to a given syntactic category ("noun" or "verb"). Two main alternative theories of performance in verb generation have been proposed, emphasizing either the competition between multiple *task-relevant* responses (e.g., Thompson-Schill & Botvinick, 2006; Thompson-Schill et al., 1997) or the effect of associative retrieval processes (e.g., Martin & Byrne, 2006; Martin & Cheng, 2006), but the respective influence of competition vs. association is unclear and still needs to be precisely assessed. Moreover,

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as we will explain, the significant effect of competition from *task-irrelevant* responses in verb generation (nouns competing with verb responses) has been largely neglected in previous studies (see also Martin & Byrne, 2006; Thompson-Schill & Botvinick, 2006).

According to the response selection/competition hypothesis (Thompson-Schill et al., 1997), the critical factor affecting verb generation performance is the degree of competition between verb responses. In this view, participants take longer to produce a verb when a noun stimulus leads to the activation of multiple incompatible representations (high selection demands condition; e.g. map → to travel, to find) than when a cue stimulus strongly activates a single response (low selection demands condition; e.g. apple → to eat). More recently, Thompson-Schill and Botvinick (2006) have framed their hypothesis within a Bayesian "competition model" of verb generation. This model relies on the strength of cue–response associations (e.g., apple–eat), on a top-down response bias (e.g., when a verb needs to be produced, activation of verbs increases and activation of nonverbs decreases), and on inhibitory connections between competing responses (e.g., to eat vs. to harvest). Preliminary results, obtained on a very simple two-layer network model of response selection on a fictitious problem, showed that response latency depends on the degree of competition (reciprocal inhibition) between the response nodes of the network. To summarize, Thompson-Schill and colleagues, while not denying the role of association, highlighted the role of competition between task-relevant responses and competition resolution processes.

In contrast, according to Martin and Cheng (2006), the critical factor for explaining verb generation performance is the strength of association between noun stimuli and verb responses. Thus, the weaker is the association between stimulus and response, the longer it takes to retrieve the response. According to this view, associative strength usually drives automatic retrieval, while more effortful and controlled search processes are activated only when automatic retrieval fails (i.e., in situations of weak stimulus–response association strength). In line with this view, Martin and Byrne (2006) have proposed a hypothetical model of verb generation that does not involve any competitive mechanism. Their hypothetical model relies exclusively on the spread of activation on associative connections between retrieval cues (noun stimulus and "action" concept in their model) and responses. Martin and Byrne claimed that their explanation should be preferred to that of Thompson-Schill and Botvinick (2006) on the basis of parsimony. Thus, according to Martin and Byrne, competition might not have a major role in verb generation (for a critical view, see Snyder & Munakata, 2008).

Some studies on verb generation investigated age-related differences (Persson et al., 2004) or performance declines in pathological groups, like frontal patients (e.g., Martin & Cheng, 2006; Thompson-Schill et al., 1998; see also Thompson-Schill, 2005) and Parkinson's disease (PD) patients (Castner et al., 2008; Crescentini et al., 2008; Péran et al., 2003). These studies are important because they offer interesting hints on the processes that underlie performance and provide useful information on the neural correlates of processing. They generally suggest that left inferior frontal areas and the basal ganglia play an important role in the verb generation task, and these same areas seem to be involved in controlled generation and retrieval and/or in the modulation of response competition (see Badre, Poldrack, Paré-Blagoev, Insler, & Wagner, 2005; Badre & Wagner, 2002; Crescentini et al., 2008; Thompson-Schill & Botvinick, 2006).

To summarize, the debate on cognitive mechanisms underlying verb generation is still unsettled (see e.g. Martin & Byrne, 2006; Thompson-Schill & Botvinick, 2006), and a better understanding of the associative and control processes underlying noun/verb generation seems necessary, considering the potential implications of this research for other generation tasks and, more in general, for generation and retrieval theories. Moreover, recent empirical evidence, briefly described in the next section of the present paper, shows that competition from *task-irrelevant* responses can strongly affect performance in the verb generation task (e.g., Crescentini et al., 2008; Thompson-Schill & Botvinick, 2006). For instance, when noun–verb associations are weak, nouns associated with the noun stimulus are likely to come to mind instead of the required verb responses (e.g., tower → castle instead of to climb). These intruding items can increase response times and, when inhibitory processes are less effective (as in Parkinson's disease: e.g., Castner et al., 2007; Copland, 2003; Longworth, Keenan, Barker, Marslen-Wilson, & Tyler, 2005), these intrusions can also decrease accuracy. However, the influence of task-irrelevant response competition has been by and large neglected in past research. Therefore, it is not appropriately considered and not convincingly explained by existing theoretical accounts of verb generation (see also Martin & Byrne, 2006).

The main goal of the present paper is to propose a novel account of noun/verb generation, grounded on the functional interaction between associative retrieval and executive control. This account aims to represent a comprehensive explanation for the main experimental findings obtained in noun/verb generation tasks on three different subject populations (young adults, older adults, and Parkinson's disease patients), offering general insights on the interaction between associative and control processes in generation tasks. A closely related aim of our study is to submit the theoretical proposal to a tight empirical validation, specifying an analytical model and fitting this model on three different datasets. This kind of test will increase the external validity of the proposed explanation and, additionally, it will prevent overfitting the model to a single dataset.

From the theoretical perspective, this conceptual and analytical effort will allow appraising in a precise way the respective role of association and competition from task-irrelevant responses and, by exclusion, to understand if it is also necessary to postulate competition from task-relevant responses in order to fully explain the observed empirical trends. The proposal will also offer a potential explanation of performance decline in older adults and PD patients within a unitary theoretical framework.

In the following section, we will present a short overview of the main empirical trends in noun/verb generation data that the model is aimed to reproduce (including our novel experimental findings). Next, a description of our theoretical account and of the Constrained Retrieval model (CoRe) will be provided. After the presentation of model fitting results, we will discuss the implications of the present study for current views of noun/verb production, the limitations of the proposed account, and more general implications of our study for the explanation of generation performance and for computational theories of retrieval.

2. Experimental findings in verb and noun generation

Martin and Cheng (2006) have recently employed a verb generation paradigm aimed at disentangling the effects of association and response competition on RT (onset latencies). These researchers compared conditions in which they varied the association strength between noun stimuli and verb responses and the presence of task-relevant (verb) competing responses (selection demands). Three conditions were thus contrasted: (i) strong association and low selection demands (A+S+), (ii) strong association and high selection demands (A+S−), and (iii) weak association and high selection demands (A−S−). The results showed that association strength affects RT (A−S− > A+S−), but the presence of competing task-relevant responses does not (A+S+ vs. A+S− ns).

We extended this paradigm to noun generation and replicated Martin and Cheng's results in a sample of 20 young adults. In our experiment, RT was significantly related to association strength but not to selection demands (see Fig. 1), both in verb generation and in noun generation. Accuracy was generally high in both tasks (>90%), but a small effect of association strength was found in verb production. Additionally, verbs were generated significantly faster than nouns in the A+S+ and A+S− conditions, but verb production was significantly slower (and accuracy lower) in the A−S− condition.[1]

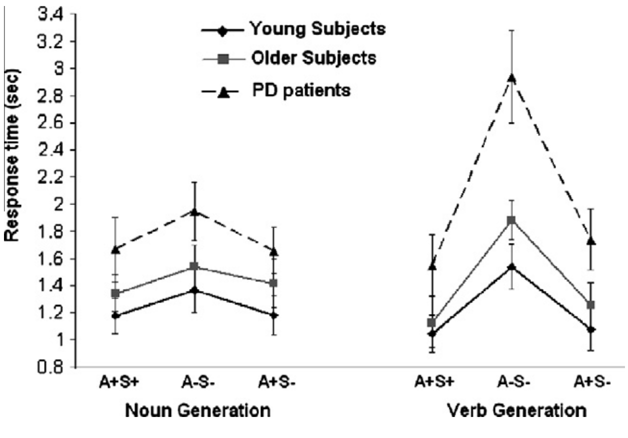

Fig. 1. Experimental results for young participants (black solid lines), older adults (grey solid lines), and PD patients (black dotted lines) in verb and noun generation. Results are plotted by experimental condition (A + S+: Strong Association-Low Selection; A−S−: Weak Association-High Selection; A + S−: Strong Association-High Selection). Error bars are 95% confidence intervals computed from data. RT is reported in seconds.

Recently, Crescentini et al. (2008) employed the same paradigm to investigate noun/verb generation in older adults and Parkinson's disease (PD) patients. Older adult data portrayed a picture very similar to the one observed in young participants (see Fig. 1, for statistical tests see Crescentini et al., 2008). However, older adults were generally slower than young participants, and this age-related difference in RT was marked in the A−S− verb generation condition, where a significant decrement in accuracy was also detected.[2]

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[1] A 2 × 3 repeated measures ANOVA with task (noun vs. verb generation) and condition (A+S+, A+S−, A-S-) as within-subject variables was carried out on RT. The ANOVA showed a main effect of condition ($F(2, 38) = 79.22$, $p < .001$) and a significant task × condition interaction ($F(2, 38) = 23.01$, $p < .001$), but the main effect of the task was not significant ($F(1, 19) = 0.89$, $p = .35$). A repeated measure ANOVA for each generation task was performed to qualify the nature of the interaction. A main effect of the experimental condition was observed both in noun generation ($F(2, 38) = 14.44$, $p < 0.001$) and in verb generation ($F(2, 38) = 86.61$, $p < .001$). Pairwise contrasts on noun generation showed significant differences between conditions A+S+ and A−S− ($F(1, 19) = 15.41$, $p < .001$), and between conditions A+S− and A−S− ($F(1, 19) = 26.67$, $p < .001$). The difference between conditions A+S+ and A+S− was instead nonsignificant ($F(1, 19) = 0.003$, $p = .95$). These contrasts highlighted a clear effect of association strength in noun generation, but no effect of selection demands. Contrasts on verb generation depicted the same pattern of findings. Significant differences were found between conditions A+S+ and A−S− ($F(1, 19) = 94.64$, $p < .001$), and between conditions A+S− and A−S− ($F(1, 19) = 108.28$, $p < .001$). As in noun generation, the difference between conditions A+S+ and A+S− was nonsignificant ($F(1, 19) = 1.27$, $p = .27$). Thus, the same pattern of differences emerges in verb and noun generation, and it is the size of these differences that qualifies the task × condition interaction. In particular, the differences in RT between the A−S− condition and the other two conditions (A+S+, A+S−) are much stronger in verb generation (491 and 459 ms) than in noun generation (190 and 183 ms). In verb generation, participants were both faster in conditions A+S+ and A+S−, and slower in condition A−S−. This is supported by pairwise contrasts comparing corresponding conditions of the two generation tasks. Young adults were indeed faster in producing verbs than nouns in conditions A+S+ ($F(1, 19) = 9.75$, $p < .007$) and A+S− ($F(1, 19) = 5.17$, $p < .05$), but they were slower in the verb production condition A−S− ($F(1, 19) = 10.37$, $p < .01$). A complete account of the experiment is available on request.

[2] Older participants were both slower and less accurate than young adults in the verb generation task (RT: $t\ (38) = -2.11$, $p < .05$; Accuracy: $t\ (38) = 2.62$, $p < .05$), less accurate in the noun generation task ($t\ (38) = 3.15$, $p < .01$), and also marginally slower in this latter task ($t\ (38) = -1.97$, $p = .06$). The differences in verb generation performance mostly depend on the A-S- condition. Only in this condition older participants were significantly slower and less accurate than young adults (RT: $t\ (38) = -3.32$, $p < .01$; Accuracy $t\ (38) = 3.19$, $p < .01$). Finally, older adults were less accurate in noun generation than young participants in the two conditions with high selection demands (A−S−: $t\ (38) = 2.90$, $p < 0.01$; A+S−: $t\ (38) = 3.17$, $p < 0.01$) and marginally so in the A+S+ condition ($t\ (38) = 1.97$, $p = 0.06$). For comparisons between older adults and PD patients and other statistical tests on these two groups see Crescentini et al., 2008.

Moreover, a minor but statistically significant effect of selection demands was also observed in verb generation.

PD patients were slower than older adults' in noun generation, and much slower in verb generation, especially in the A−S− condition. In verb production, they exposed a very strong effect of association strength and a minor (but statistically significant) effect of selection demands (see Fig. 1, for statistical tests see Crescentini et al., 2008). PD patients were also always less accurate in verb generation than in noun generation. They were particularly impaired in the A−S− condition of verb production, due to a relatively high number of syntactic errors (noun instead of verb response: see Crescentini et al., 2008, Fig. 5). These 'intrusion' errors probably originate from a failure to inhibit task-irrelevant responses (see also Thompson-Schill & Botvinick, 2006). Free association norms for experimental stimuli provided independent support for this idea: nouns were spontaneously produced much more often than verbs, and this tendency was stronger for the A−S− verb generation condition (Crescentini et al., 2008, Fig. 2).

To summarize (see also Fig. 1), a strong influence of S–R association strength on RT was found in noun and verb generation in three different populations, and this represents a first general trend in the data. A second general trend is that the difference in RT between the condition with weak S–R associative strength (A−S−) and the conditions with stronger S–R associations (A+S+, A+S−) is exacerbated in the verb production task. The third main empirical tendency is that verb generation is faster than noun generation in the conditions with strong S–R associative strength. However, this trend is reversed in the A−S− condition, in which verbs are actually more difficult to produce than nouns (lower accuracy and higher RT). Again, this generally holds for the three populations examined.

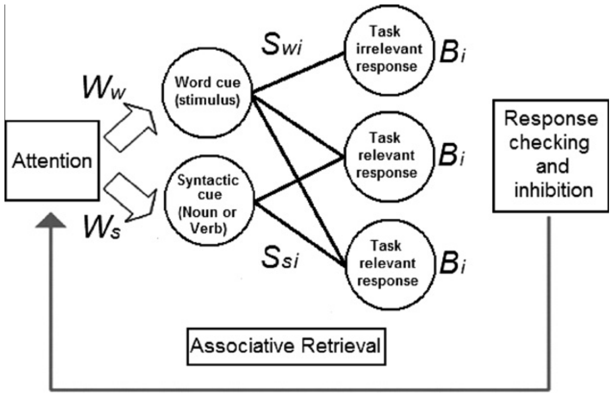

Fig. 2. Main components and processing steps of the model. The specific network topology represents a situation in which two task-relevant responses and one task-irrelevant response are associated to a stimulus (word cue). W_w and W_s indicate the degree of attentional resources allocated to the word cue and the syntactic cue, respectively. S_{wi} and S_{si} designate the associative strengths for the links connecting the word and syntactic retrieval cues to the response nodes, and B_i represent base-rate activations of response nodes.

In addition to these three general trends, there are significant population-related differences. First, RT generally increases from young to older adults and from older adults to PD patients. This is accompanied by a corresponding decrease in the accuracy of verb generation, which is striking in the A−S− condition (see Fig. 3 in Crescentini et al., 2008). In this condition, PD patients show a high proportion of intrusion errors in verb production, and they are generally very slow and inaccurate. Finally, in verb generation, PD patients and (to a lesser extent) older adults expose a difference in RT suggestive of the influence of selection demands.

3. A novel account of verb and noun generation

The account proposed in the present paper combines a standard model of associative retrieval, based on the ACT-R theory (Anderson & Lebiere, 1998; Anderson et al., 2004), with the ideas of strategic allocation of attention on retrieval cues and intentional inhibitory processes (e.g., Miyake et al., 2000; Stuss et al., 2005). The postulated control processes play a functional role in regulating retrieval.

According to our view, S–R association strength is a fundamental determinant of noun/verb generation performance, and a simple multiple-cue retrieval process has a remarkable explanatory power (see also Martin & Byrne, 2006). However, we also deem necessary to postulate the action of intentional inhibitory processes, which are needed to block task-irrelevant responses after retrieval (e.g., a noun when a verb is required) and to allow a new retrieval attempt to take place, after the strategic re-allocation of attention on retrieval cues.

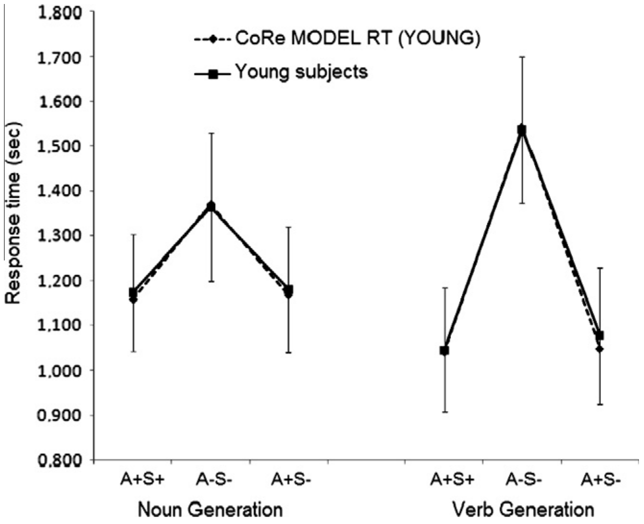

Fig. 3. Experimental results for young participants in verb and noun generation (solid lines) and model predictions for RT (dotted lines). Results are plotted by experimental condition (A + S+: Strong Association-Low Selection; A−S−: Weak Association-High Selection; A + S−: Strong Association-High Selection). Error bars are 95% confidence intervals computed from data. RT is reported in seconds.

More specifically, our view of noun/verb generation (Fig. 2) assumes three processing stages: (1) allocation of attention on (word and syntactic) retrieval cues, (2) automatic associative retrieval via spreading activation, (3) response checking and inhibition. Finally, we also postulate that initiating a new retrieval attempt implies the strategic re-allocation of attention. We will first describe the postulated control processes and then focus on associative retrieval.

3.1. Control processes

Following Martin and Byrne (2006), we assume that noun/verb generation depends on two retrieval cues: a word cue and a syntactic cue (qualifying the target response category as “noun” or “verb”). In a conventional semantic network representation (Fig. 2), cues and potential responses are connected by links with associative strength. A simple but powerful form of retrieval control consists in the strategic allocation of attentional resources on the word cue vs. the syntactic cue.

We assume that resources available for retrieval (source activation) are limited (e.g., Anderson et al., 2004) and that they are shared between the two cues, with the word cue initially getting more attention (see next section). If a task-irrelevant (wrong) response is retrieved, more attention is placed on the syntactic cue at the expenses of the word cue in the next retrieval attempt. This re-allocation of attentional resources is functionally motivated by the need to overcome what we deem to be the most frequent cause of retrieval error (intrusion of task-irrelevant responses). In fact, giving more attention to the syntactic cue increases the probability of retrieving a correct response. Different (and perhaps more complex) strategies may be used when no response is retrieved (e.g., Martin & Byrne, 2006). In any case, the strategic allocation of attention on retrieval cues involves a time cost.

The second control process is a simple response-checking mechanism, which has the function of verifying the correctness of the retrieved items and of inhibiting the production of task-irrelevant responses (e.g., Miyake et al., 2000; Stuss et al., 2005). This mechanism is justified by the accrual of evidence showing that task-irrelevant responses tend to intrude in noun and verb generation when the S–R associations between the stimulus and correct responses are weak (Crescentini et al., 2008; Thompson-Schill & Botvinick, 2006). Besides requiring time, this control mechanism can sometimes fail. We hypothesize that its accuracy is related to the efficiency of intentional inhibitory processes, which can significantly decline in pathological conditions like PD (e.g., Castner et al., 2007, 2008; Copland, 2003).

3.2. Associative retrieval

Our associative account of noun/verb generation is based on the ACT-R theory, which has proved able to explain a wide array of experimental findings in memory research (Anderson, Bothell, Lebiere, & Matessa, 1998; Anderson & Lebiere, 1998). However, similar principles characterize other associative memory theories. Retrieval is initiated by paying attention on the word cue and the syntactic cue. Activation spreads in the network from these two cues, reaching potential response nodes. The final activation of a response node depends on its baseline strength (base-rate activation), on the number and strengths of its incoming associative links from activated retrieval cues, and on the attention initially placed on retrieval cues (cf. Danker, Gunn, & Anderson, 2008).

Eq. (1) shows how the activation of target words is computed in the specific case of noun/verb generation. In this equation, A_i is the activation of the response node i, B_i is the node base-rate activation, W_w is the attentional weight placed on the word (stimulus) cue, W_s is the attentional weight placed on the syntactic cue, and S_{wi} and S_{si} are the associative strengths of the links connecting the response node with the word and syntactic cues, respectively.

$$A_i = B_i + W_w S_{wi} + W_s S_{si} \tag{1}$$

The time needed to retrieve from memory a particular response (T_i) is related only to the final activation of its node (A_i), as the following ACT-R equation makes clear (F is a scaling factor parameter):

$$T_i = Fe^{-A_i} \tag{2}$$

As anticipated, the word cue (W_w) initially gets more attention than the syntactic cue (W_s). This is partly related to the way the generation task was administered in our experiments: while the syntactic cue (“verb” or “noun”) was presented only at the beginning of each block of trials (and had to be kept in mind), the specific word cues were more salient to the participants (being presented one by one within each block of trials). Strategic re-allocation gradually shifts attention from the word cue to the syntactic cue in subsequent retrieval attempts (i.e., only after a wrong response is retrieved), in order to overcome interference from task-irrelevant competitors and to allow the generation of a correct response. However, attentional resources available for retrieval (W) remain constant across attempts ($W_w + W_s = W$). Previous studies modeled individual differences in memory tasks though a variation in the attentional resources that can be allocated for retrieval (e.g., Daily, Lovett, & Reder, 2001; Lovett, Reder, & Lebiere, 1999). We similarly hypothesize that a population-related reduction in retrieval-related attentional resources can contribute to the explanation of RT differences in noun/verb generation (e.g., Brown & Marsden, 1988; Lee, Grossman, Morris, Stern, & Hurtig, 2003; Persson et al., 2004; Wierenga et al., 2008).

According to the ACT-R theory, the association strength of a link stemming from a source node is inversely related to the fan of this source node (i.e., the higher the number of nodes connected to the source node, the lower is the associative strength of each link; e.g., Anderson, 1974; Danker et al., 2008; Sohn, Anderson, Reder, & Goode, 2004). Thus, given that there are more nouns than verbs in the lexicon, the associations between the "verb" syntactic cue and verb responses (S_{si}) will be stronger than the associations between the "noun" syntactic cue and noun responses. Thus, *ceteris paribus*, the syntactic cue "verb" will be more effective than the syntactic cue "noun" due to its smaller associative fan.

4. The constrained retrieval (CoRe) model

Relying on the theoretical account just outlined, we specified a simple analytic model aiming to predict RT in correct trials. We intentionally made bold simplifications, in order to show that basic associative principles can provide a good explanation (for instance, no decay or accumulation of activation is explicitly modeled). However, a more realistic account should include sophisticated forms of dynamic and stochastic variation in activation. The CoRe model is based on Eqs. (1) and (2). We assume that a single retrieval attempt is usually needed to produce a correct response. In this case, the final RT is simply the sum of stimulus encoding time (E), allocation of attention on retrieval cues (A), retrieval time (computed according to the Eqs. (1) and (2)), response checking time (RC), and response preparation time (R). Eq. (3) summarizes the model (E, A, RC and R are fixed parameters, T_i is retrieval time):

$$RT_i = E + A + T_i + RC + R \tag{3}$$

However, particularly in A−S− experimental conditions, multiple retrieval attempts may be needed to produce a correct response, because task-irrelevant responses have a stronger tendency to intrude. In this case, the final RT combines encoding and response preparation times, multiple retrieval times (including time to retrieve wrong items), response checking times, and time to strategically allocate attention before each retrieval attempt. The final RT is given by Eq. (4), in which j is the retrieval attempt (ranging from 1 to a reasonable maximum of three per trial in PD data) and n is the total number of retrieval attempts. Retrieval time can vary in different attempts, due to the effect of attention re-orientation on cues.

$$RT = E + nA + \sum_{j=1}^{n} T_j + nRC + R \tag{4}$$

We fitted the CoRe model to mean RT data from the three populations involved in our studies (young adults, older adults, and PD patients). This represents a challenging test, given that a complex pattern of findings needs to be reproduced (18 RT means depicting nonlinear relationships).

4.1. Model parameters

Two free parameters were allowed to vary in a *theoretically-constrained manner*. First, according to our hypothesis that population-related differences in attentional resources allocable for retrieval contribute to differences in RT, the value of the W parameter was decreased across populations, from its standard value (Anderson & Lebiere, 1998) to lower values in older adults and PD patients. Second, according to our hypothesis that in A−S− conditions more retrieval attempts are needed to overcome interference from task-irrelevant stimuli, we varied the number of retrieval attempts carried out in different experimental conditions. In particular, we fixed the value of this parameter at one in the A+S+ and A+S− conditions, and increased it only in the more intrusion-prone A−S− conditions. We also slightly increased the number of additional retrieval attempts from younger adults to older adults, and from older adults to PD patients, because the population-related decrease of attentional resources makes intrusions more likely in the A−S− condition.[3]

We established the values of fixed parameters (including associative components) from independent data sources or from previous studies. Encoding time ($E = 150$ ms) was fixed following Kieras, Meyer, Mueller, and Seymour (1999) and word identification estimates (e.g., Rayner & Pollatsek, 1989). The attention allocation time ($A = 200$ ms) is in line with the time estimates of attention shift in previous studies based on the ACT-R theory (e.g. see Anderson, Matessa, & Lebiere, 1997; see also Altmann & Trafton, 2002). The time needed to check a retrieved response and to inhibit it ($RC = 150$ ms) was fixed considering the time cost of a typical intentional inhibition task with verbal response (Stroop: Friedman & Miyake, 2004; Miyake et al., 2000). The onset of the vocal response for young adults (response time: $R = 100$ ms) was established in agreement with EPIC values for verbal output (see Kieras & Meyer, 1997, p. 407; Kieras et al., 1999, p. 193). This value was increased by a factor of 1.5 in older adults (cf., Buchler, Hoyer, & Cerella, 2008, p. 747), who are usually slower in their responses. Finally, the R parameter was further increased in PD patients (450 ms), given the longer time needed by these patients for response programming and initiation (e.g., Cooper, Sagar, Tidswell, & Jordan, 1994; see also Péran et al., 2003).

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[3] This is easy to explain analytically by referring to Eq. (1). While the full Eq. (1) holds for target responses, activation of foil (interfering) responses depends only on the leftmost part of the equation ($B_i + W_w S_{wi}$), given that the associative part related to the syntactic cue is zero (because there is no S_{si} link to syntactically incorrect responses). Now, let's assume that B_i (base-rate activation) and S_{wi} (stimulus-response association) have similar values for a target and a foil (a competition situation). If W is decreased, then, the difference in activation between the target and the foil is reduced proportionally (due to the reduction of the associative component of the equation, $W_s S_{si}$, which is relevant only for targets but not for foils). This means that target and foil activation values will become closer and that, assuming stochastic variations in activation values (e.g., Anderson & Lebiere, 1998; Anderson et al., 2004), it will be more likely that a foil is retrieved instead of a target (vs. the full attentional resources situation; i.e., $W = 1$). The difference in target vs. foil activation will be even smaller if the stimulus-foil association is relatively stronger than the stimulus-target association (a condition close to the A−S− condition). An excel simulation showing this pattern with realistic parameter values is available upon request.

Other fixed parameters concerned the associative component of the model. Median base-rate activation of noun and verb responses (*B*) were derived from ln-transformed frequencies (normalized: Szekely et al., 2005) taken from the Veli Dictionary of Frequency for Italian Spoken Language. S–R association strength in noun–noun and noun–verb tasks were taken from the pretest study in Crescentini et al. (2008, pp. 437–438). Association between syntactic nodes (“noun” and “verb”) and potential responses were computed by relying on scaled relative frequency of noun and verb synsets (sets of cognitive synonyms) in the WordNet database (Fellbaum, 1998). Finally, the scaling factor for RT (*F*, which is usually a free parameter in ACT-R models) was established in the young adults dataset ($F = 2.1$), considering both the model fit and the general appropriateness of mean retrieval time estimates, and kept constant in the other populations.

Table 1
Model fitting results for three datasets (young adults, older adults, and PD patients).

	Young adults		Older adults		PD patients	
	CoRe	Baseline	CoRe	Baseline	CoRe	Baseline
RMSE	0.01	0.16	0.06	0.31	0.07	0.63
MAD	0.01	0.09	0.05	0.24	0.04	0.42
R^2	1.00	0.39	0.95	0.29	0.98	0.06
95%_CI_out	0	17%	0	50%	0	50%

Note: The CoRe model instantiates the theoretical account described in the paper. The fixed parameters of the CoRe and Baseline models are identical (for corresponding populations and conditions). However, in the Baseline model, attentional resources available for retrieval are kept fixed across populations ($W = 1$) and a single retrieval attempt is allowed in each experimental condition. RMSE is the root mean squared error, MAD is the mean absolute difference, and 95%_CI_out is the percentage of predictions outside the 95% confidence intervals computed from data (on a total of six for each population).

4.2. Results

The results of analytical modeling, carried out with an Excel spreadsheet,[4] are summarized in Table 1 and Figs. 3-5. The CoRe model accurately reproduced participants’ RT performance, capturing a complex pattern of findings on two different tasks in three populations (and this precluded overfitting the data to a peculiar population or condition). Each predicted mean falls within the 95% confidence intervals estimated from data. Quantitative measures, computed on series of six means, confirm the good fit of the model (see Table 1).

The theoretically-relevant free parameters (the number of additional retrieval attempts and *W*) provided a significant contribution to the model fit (see Table 2). Indeed, zeroing the number of additional retrieval attempts in A−S− conditions produced a marked decrease in adaptation. Not decreasing attentional resources across populations (i.e., fixing $W = 1$) also decreased the model fit, although to a much lesser extent. Thus, as hypothesized, both factors contribute to explaining generation performance, but the number of additional retrieval attempts in A−S− conditions seems to be the most important determinant of RT differences. Finally, sensitivity analysis showed that model fitting results are robust to moderate-to-strong variations in parameter values.[5]

5. General discussion

5.1. Explanation of performance, limitations, and relationship with previous accounts of noun/verb generation

According to modeling results, the theoretical proposal presented in this paper represents a good general account of RT performance in verb and noun generation. The associative kernel of the CoRe model naturally explains the influence of S–R associations on RT. The need to overcome interference from task-irrelevant responses through multiple retrieval attempts accounts for the peculiar difficulty of verb generation in the A−S− condition and explains why a single-retrieval associative model is not able to fit the data appropriately (see Table 2). Finally, the greater associative fan of the “noun” syntactic cue (vs. the “verb” syntactic cue) clarifies why verb generation is faster than noun generation in conditions with strong S–R associative strength. Population-related differences are explained by the stronger interference from task-irrelevant associates in the A−S− conditions, which is possibly related to a reduction in attentional resources that can be allocated for retrieval (and, perhaps, for retrieval control). As a consequence, older adults need some more attempts (and PD patients even more) in order to be able to generate an appropriate response.

In the present paper we did not focus on accuracy data, because this would have required the development of a more complex simulative model. However, the proposed theoretical account could naturally explain accuracy results. Participants are indeed less accurate in the A−S− verb generation condition, in which interference from task-irrelevant associates is more severe. Due to this interference, participants are not only slower, but they may sometimes miss the response deadline (young and older adults), or they may output a task-irrelevant response if the efficiency of their inhibitory processes is seriously reduced by Parkinson’s disease (e.g., Castner et al., 2007; Copland, 2003; Longworth et al., 2005; see below in this section).

However, the model presented and tested in this paper seems to have at least one significant shortcoming. Our associative account was indeed unable to reproduce the small RT difference suggestive of a selection effect (A+S− vs. A+S+) observed in PD patients’ and older adults’ verb generation (see Figs. 1, 4 and 5). Experimental results

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[4] The model spreadsheet is available upon request.

[5] Additional information on model parameters and sensitivity analysis is available on request.

Table 2
Decrease in fit (in absolute value) due to the orthogonal manipulation of the two theoretically-relevant free parameters: (1) zeroing the number of additional retrieval attempts in A–S– conditions (*R* models), or (2) not decreasing attentional resources available for retrieval across populations (*W* models).

	Young adults	Older adults			PD patients		
	R	*R*	*W*	*R* & *W*	*R*	*W*	*R* & *W*
RMSE_d	0.15	0.21	0.07	0.25	0.49	0.15	0.56
MAD_d	0.08	0.13	0.07	0.19	0.26	0.16	0.38
R^2 d	0.61	0.78	0.00	0.66	0.98	0.01	0.92
95%_CI_out	17%	33%	17%	50%	33%	17%	50%

Note. All the measures in the table (with the exception of 95%_CI_out) represent absolute *differences* in fit: RMSE_d (increase in root mean squared error), MAD_d (increase in mean absolute difference), and R^2 *d* (decrease in R^2). Models used as baseline for comparisons are CoRe best-fitting models for specific populations (in which both parameters are kept fixed to their best-fitting values).

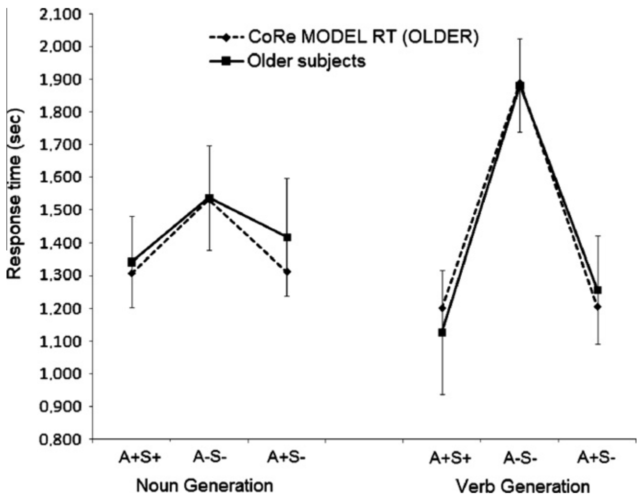

Fig. 4. Experimental results for older participants in verb and noun generation (solid lines) and model predictions for RT (dotted lines). Results are plotted by experimental condition (A + S+: Strong Association-Low Selection; A–S–: Weak Association-High Selection; A + S–: Strong Association-High Selection). Error bars are 95% confidence intervals computed from data. RT is reported in seconds.

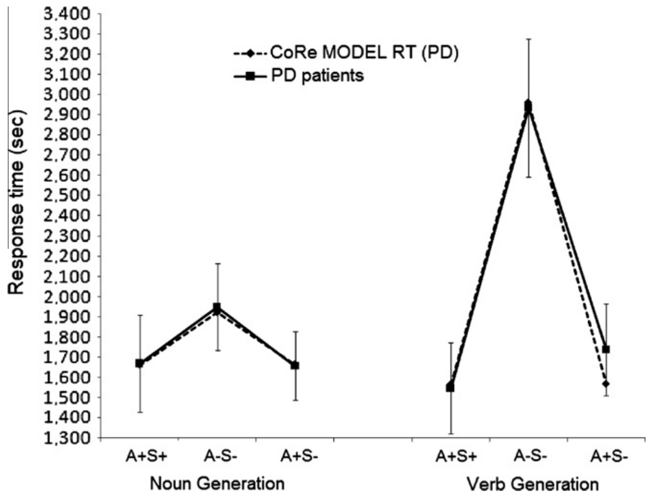

Fig. 5. Experimental results for PD patients in verb and noun generation (solid lines) and model predictions for RT (dotted lines). Results are plotted by experimental condition (A + S+: Strong Association-Low Selection; A–S–: Weak Association-High Selection; A + S–: Strong Association-High Selection). Error bars are 95% confidence intervals computed from data. RT is reported in seconds.

reported in the present paper suggest that, at least in the case of strong S–R association strength (see Fig. 1, A+ conditions), the competition between task-relevant responses may be normally handled without much effort in young adults, who possibly rely on very efficient selection processes (e.g., Nigg, 2000; Thompson-Schill & Botvinick, 2006). Our previous findings and other studies instead indicate that resolution of this competition may be slightly but significantly more challenging for older adults and neuropsychological patients (e.g., Castner et al., 2008; Crescentini et al., 2008; Persson et al., 2004; Thompson-Schill et al., 1998). For instance, Thompson-Schill et al. (1998) administered the verb generation task to a sample of patients with focal frontal lesions. The authors found that patients with lesions involving the left posterior region of the inferior frontal gyrus (pIFG) were specifically impaired in the high selection demands condition relative to patients with lesions of other areas in the frontal lobe. The potential role of task-relevant competition would be also compatible with other recent behavioral findings (Snyder & Munakata, 2008) and with an fMRI study on noun/verb generation carried out on young adult participants (Crescentini, Shallice, & Macaluso, 2009). This fMRI study showed that the posterior part of the left IFG (left mid/posterior ventrolateral prefrontal cortex, VLPFC) was involved in the selection of task-relevant competing responses even when no effect of selection demands was detected in RT data (A+S– = A+S+).

On the other hand, in this study, neuroimaging data showed that the left basal ganglia are particularly active when task-irrelevant stimuli interfere with the current task (e.g., nouns during verb generation), particularly in the A–S– verb generation condition (Crescentini et al., 2009). Additionally, the same study showed that the more anterior section of the left VLPFC was also selectively involved in the A–S– condition of verb generation. The former finding provided further evidence that basal ganglia play a significant role in attention modulation and inhibition in the domain of language and semantic retrieval (e.g. Copland, 2003; Longworth et al., 2005; for other domains see, e.g., Brown, Soliveri, & Jahanshahi, 1998; Yehene, Meiran, & Soroker, 2008). In the context of the CoRe model, this suggests that population-related differences in verb/noun generation may partly depend on processing carried out in the basal ganglia and, more generally, on the status of the dopaminergic neurotransmitter system, which is well known to be compromised in PD patients (e.g. Owen, 2004). Notably, there is a considerable body of research linking dopamine levels in fronto-striatal circuits to performance on working memory and attentional selection tasks (e.g. Braver & Cohen, 2000; McNab & Klingberg, 2008; Nieoullon, 2002). Generally speaking, optimal dopaminergic transmission seems to contribute to attention focusing and filtering of irrelevant information, while dopaminergic problems would produce attentional impairments. In terms of the CoRe model, the left basal ganglia and the anterior/ventral VLPFC may work in concert during the attentional modulation of control, which is particularly required by the interference-prone A−S− verb condition (Crescentini et al., 2008; see also McNab & Klingberg, 2008 and Badre et al., 2005).

To summarize, while S–R associations play a central role in noun/verb generation performance, and task-irrelevant competition has a strong effect in specific conditions (which is amplified in peculiar populations), competition between task-relevant responses probably exerts a significant influence at least in peculiar populations or situations. Future work could expand our theoretical account in order to explain also task-relevant competition, for instance by including the influence of inhibitory connections (cf. Thompson-Schill & Botvinick, 2006) or by proposing other mechanisms that underlie the selection of task-relevant responses. To conclude, the present study supports the view that two factors identified by previous accounts of verb generation (association strength, competition from task-relevant responses) are significant determinants of RT performance, together with a third important factor that has been by and large neglected in previous research (competition from task-irrelevant responses).

5.2. Future work and relationships with computational theories

It is worth underlining that the theoretical value of the proposed explanation is not limited to noun/verb generation performance. First, the account can be easily generalized to a variety of generation tasks (like category fluency or option generation), because it relies on a general view of the interaction between associative processes and control mechanisms. Also in these different generation contexts, the model can help us to understand the relative role of association and response competition and, if properly expanded, it could represent a unifying explanation for different kinds of empirical effects. Additionally, the present account shows promising directions for the explanation of individual and population-related differences in generation performance, which we assume to be partly related to the greater vulnerability to interfering memories, in line with existing empirical evidence (e.g., Crescentini et al., 2008; Hartley & Walsh, 1980; Kahana, Dolan, Sauder, & Wingfield, 2005; Kahana, Howard, Zaromb, & Wingfield, 2002).

The theoretical proposal presented in this paper may also represent a good starting point for investigating control processes in multiple-cue memory retrieval, which are still rather poorly understood. In this respect, the present account could be also generalized beyond verb generation to different semantic and episodic memory paradigms and tasks. A good candidate would be the fan paradigm (e.g., Anderson, 1974; Sohn et al., 2004). Although the present paper purposely focused on noun/verb generation, extending the model to other memory paradigms may reveal deep commonalities in control and associative mechanisms involved in different tasks, and thus advance our knowledge of general memory principles (Surprenant & Neath, 2009). In this regard, it is interesting to note that, being based on a general model of associative retrieval, our proposed account bears clear resemblances with retrieve/test process models of recall (like the Search of Associative Memory: Raaijmakers & Shiffrin, 1981; see also Raaijmakers, 2003), which posit an associative process of sampling candidates for recall followed by a subsequent editing/recognition process.

Another aspect that deserves to be discussed is the relationship between the general aspects of the model described in the present paper and major features of cognitive architectures that have been proposed as unifying computational accounts of memory and control processes, like ACT-R (Anderson & Lebiere, 1998; Anderson et al., 2004), SOAR (Laird, 2008; Lewis, 2001), EPIC (Kieras & Meyer, 1997; Kieras et al., 1999; Meyer & Kieras, 1997), and CLARION (Sun, 2006, 2007). This specific aspect of the discussion can be stimulating for readers interested in computational modeling of cognitive processes, because it can be informative about potential strengths/limitations of these general accounts of cognition. It should be noted that the model described in the present paper is a high-level analytical account and not a specific computational model. However, it can be possibly ‘translated’ into an ACT-R model, given the common associative theoretical background. In this case, it would be necessary to specify the control components (response checking and inhibition, modulation of attentional focusing), a task that will probably require further specification. Moreover, given that ACT-R does not explicitly include inhibitory links, a potential generalization of the model that includes this form of inhibition (e.g., Thompson-Schill & Botvinick, 2006) will require major theoretical modifications of the ACT-R theory. It is likely that such modifications will revive the (still) unsettled theoretical debate between proponents and opponents of cognitive inhibition (see e.g. Gorfein & MacLeod, 2007).[6]

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[6] It is also worth noting that applying these modifications is probably not complex from the mathematical/technical viewpoint: inhibitory effects might be obtained in ACT-R as a normalization process on target activation, which takes into account the activation of the potential competitors (i.e., the time to retrieve a response is not dependent only on its activation, but on the activation of its competitors as well). We thank an anonymous reviewer for pointing out this possibility.

According to our opinion, other architectures will probably encounter greater problems if attempting to ‘translate’ the model presented in this paper, due to their more general and less empirically tested specifications of associative memory (e.g., CLARION, but in particular SOAR and EPIC). On the other hand, all these architectures (including ACT-R) seem to be well-equipped for capturing the intentional control processes coping with task-irrelevant competition (that can be modeled by production rules or explicit control processes). Finally, none of these architectures seems to explicitly postulate the presence of potential inhibitory connections within associative memory (but CLARION can possibly overcome this limitation at the implicit level). To conclude, the data coming from the noun/verb generation task and existing theoretical explanations (including the one described in the present paper) pose difficult but exciting challenges for cognitive architectures embedding memory theories. We hope that these challenges could stimulate further research on generation tasks and thus advance our knowledge of the interaction between associative and control processes in memory retrieval.

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