



## Original Articles

# A unified computational account of cumulative semantic, semantic blocking, and semantic distractor effects in picture naming

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## ABSTRACT

Computational models of lexical selection in spoken word production have been applied to semantic interference effects in picture naming response times obtained with continuous naming, blocked-cyclic naming, and picture-word interference paradigms. However, a unified computational account of the effects in the three paradigms is lacking. Here, I show that the inclusion of conceptual bias in the WEAVER++ model (Levelt, Roelofs, & Meyer, 1999) explains cumulative semantic and semantic blocking effects while preserving the model's account of semantic distractor effects. The key assumptions of the account are (1) lexical selection by competition, and (2) a conceptual origin and lexical locus of the semantic effects. I provide a proof of concept of the account by reporting computer simulation results, addressing behavioral and neuroimaging evidence. The assumptions are sufficient for a unified account of semantic effects in the three paradigms, contrary to pessimistic views of this area.

## 1. Introduction

In situations as different as naming pictures and holding conversations, speakers activate and select words in long-term memory based on conceptual information, and listeners retrieve the conceptual information for the words when they are heard. It is often assumed that the cognitive and neural mechanisms underlying lexical selection are shared between picture naming and having a conversation (e.g., Levelt, 1989; Roelofs, 2014). Over the past few decades, lexical selection in spoken word production has been intensively investigated, first using picture-word interference (e.g., Schriefers, Meyer, & Levelt, 1990), and later using blocked-cyclic naming (e.g., Belke, Meyer, & Damian, 2005) and continuous naming paradigms (e.g., Howard, Nickels, Coltheart, & Cole-Virtue, 2006). These studies concentrated on semantic interference from categorical relatedness in picture naming (e.g., selecting the word *fork* in the context of *glass* or *spoon* of the category tableware): Response time (RT) is longer and accuracy is lower in semantically related than in unrelated contexts. Computational models of lexical selection were developed to account for the key findings obtained with these paradigms, in particular, cumulative semantic interference in continuous naming, semantic interference in blocked-cyclic naming, and semantic interference from distractor words in picture-word interference studies. However, computational models developed for picture-word interference (e.g., Roelofs, 1992) have not been applied through computer simulations to findings from the other paradigms yet.

Similarly, computational models of cumulative semantic and semantic blocking effects (e.g., Howard et al., 2006; Oppenheim, Dell, & Schwartz, 2010) were not applied to picture-word interference.

Howard et al. (2006) argued that in their current forms, computational models of lexical selection such as WEAVER++ (Levelt, Roelofs, & Meyer, 1999; Roelofs, 1992) “are falsified by” (p. 464) the cumulative semantic effects. According to them, modifying these models to accommodate the effects is “a non-trivial exercise for modellers of the speech production process for two reasons: (a) will such modifications harm the models’ abilities to simulate data which they can currently simulate? and (b) will these modifications actually succeed in simulating the cumulative semantic inhibition effect? Only future modelling work can tell us the answers to these two questions” (Howard et al., 2006, p. 479).

The aim of the present article is to demonstrate that the WEAVER++ model is not falsified but incomplete. I show that a simple extension of WEAVER++, namely the inclusion of conceptual bias, accounts for cumulative semantic and semantic blocking effects while preserving the model's account of semantic distractor effects. The key assumptions of the unified account are that (1) lexical selection is by competition, and (2) the origin of the semantic effects is at the conceptual level and the locus is in lexical selection (cf. Belke, 2013; Roelofs, 1992). I provide a proof of concept of the account by reporting computer simulation results.

These two key assumptions played an important role in explaining

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semantic effects in the picture-word interference paradigm (e.g., Levelt et al., 1999; Roelofs, 1992), and the present article shows that these assumptions also explain cumulative semantic and semantic blocking effects. However, researchers hotly debate the assumptions in the literature. Picture naming involves perceptual and conceptual encoding, lexical selection, word-form encoding, and finally articulation. Word-form encoding includes morphological, phonological, and phonetic encoding (e.g., Levelt et al., 1999). Alternative accounts of picture-word interference assume an origin and locus of the semantic interference effect in perceptual and conceptual encoding (Dell'Acqua, Job, Peressotti, & Pascali, 2007; Van Maanen, van Rijn, & Borst, 2009) or in an articulatory buffering stage after phonetic encoding (Finkbeiner & Caramazza, 2006). Alternative accounts of cumulative semantic and semantic blocking effects assume a lexical locus but an origin in the links between concepts and lexical items (Howard et al., 2006; Oppenheim et al., 2010) or an origin at the lexical level (Damian, Vigliocco, & Levelt, 2001). Here, I assume a conceptual origin and a lexical locus, following WEAVER++'s account of semantic distractor effects and Belke's (2013) account of cumulative semantic and semantic blocking effects (see also Harvey & Schnur, 2016).

The wording "origin versus locus" of an effect was proposed by Belke (2013) and adopted by others (e.g., Harvey & Schnur, 2016). The origin of the cumulative semantic or semantic blocking effect refers to the level at which the structural change underlying the effect occurs, for example, a change in the strength of connections between concepts and lexical items (Howard et al., 2006; Oppenheim et al., 2010) or between concepts (Belke, 2013). The locus of the effect refers to the level at which the behavioral consequence arises, which is the level of lexical selection in picture naming according to all existing theories.

The remainder of this article is organized as follows. Section 2 describes the continuous naming, blocked-cyclic naming, and picture-word interference paradigms together with the key findings obtained with these paradigms. Several findings are robust in that they have been replicated by different labs, whereas some findings are still controversial. Section 3 explains the conceptual bias assumption and indicates how the assumption is implemented in the WEAVER++ model. Section 4 reports the results of computer simulations that assessed the utility of the model to account for findings from picture naming, picture classification, word naming, and word naming with a gender-marked determiner in experiments that assessed cumulative semantic effects. Behavioral as well as neuroimaging data are discussed. Also, the model is applied to data from blocked-cyclic naming and picture-word interference. Moreover, the models of Howard et al. (2006) and Oppenheim et al. (2010) are evaluated using key findings from picture-word interference, and some challenges for these models are outlined.

## 2. Cumulative semantic, semantic blocking, and semantic distractor effects

### 2.1. Basic empirical findings

In a continuous naming experiment (e.g., Belke, 2013; Costa, Strijkers, Martin, & Thierry, 2009; Howard et al., 2006), participants name pictures drawn from several semantic categories (e.g., tableware, birds, tools). Pictures are not repeated but there are several exemplars from each category, typically five (e.g., fork, spoon, glass, cup, knife; swan, owl, duck, eagle, parrot; axe, drill, hammer, saw, screwdriver). Pictures of different categories are mixed across trials, with varying numbers of unrelated pictures occurring between the category members. The picture naming RT is assessed for each ordinal position within a category. For example, if the trial sequence consists of a picture of a fork followed by a number of unrelated pictures and a spoon, then the fork is in first position within the category tableware and the spoon is in second position, as illustrated in Fig. 1A.

The key finding is that naming RT increases linearly with ordinal position, that is, linearly as a function of the number of previously

named pictures in a particular category. This cumulative semantic interference effect is independent of the exact number of other unrelated pictures that occur between each category exemplar if it ranges between two and eight (i.e., lags of two, four, six, and eight intervening unrelated pictures). However, the cumulative semantic effect disappears when the number of intervening unrelated pictures is consistently larger than eight (Schnur, 2014). Note that with lags between two and eight, semantic categories come in waves in an experiment with different categories partly overlapping. Once the first exemplar of a category is presented, all other exemplars of the category occur within the next 25 trials.

In a blocked-cyclic naming experiment (e.g., Belke et al., 2005; Harvey & Schnur, 2016; Schnur, Schwartz, Brecher, & Hodgson, 2006), participants repeatedly cycle (typically six times) through naming a small set of pictures (often five pictures). In homogeneous cycles, all pictures are drawn from the same semantic category (e.g., tableware, birds, tools), and in heterogeneous cycles, the pictures are from different semantic categories. The pictures in the semantically homogeneous and heterogeneous conditions are the same, but their grouping differs. Thus, the blocking effect is tested within items. Fig. 1B illustrates the trial sequence within a blocked-cyclic naming experiment.

The key finding is that naming RT is longer in the semantically homogeneous condition (e.g., naming a fork, glass, spoon, cup, and knife) than in the heterogeneous condition (e.g., naming a fork, swan, axe, bed, and mouth). This semantic interference effect is typically not present in the first cycle, where usually no blocking effect, or instead semantic facilitation, occurs (e.g., Navarrete, Del Prato, Peressotti, & Mahon, 2014; see Belke, 2017, for a review). Also, the semantic interference effect may increase over subsequent cycles, although this increase is typically not observed in healthy speakers (see Belke & Stielow, 2013, for a review).

In a picture-word interference experiment (e.g., Glaser & Dünghoff, 1984; Rayner & Springer, 1986), participants name pictures (typically some 20–30 drawn from several semantic categories) while trying to ignore written or spoken distractor words. For example, they say "fork" to a picture of a fork combined with the semantically related word *glass* or the unrelated word *swan*. Fig. 1C illustrates the trial sequence within a picture-word interference experiment.

The key finding is that naming RT is longer on semantically related than on unrelated trials (e.g., Damian & Martin, 1999; Glaser & Dünghoff, 1984; Rayner & Springer, 1986; Schriefers et al., 1990). When the stimulus onset asynchrony (SOA) between picture and written word is manipulated, the semantic interference effect is maximal at short SOAs (i.e., with word preexposure or postexposure by 100 ms or less) and it decreases when SOA becomes longer (e.g., Glaser & Dünghoff, 1984).

### 2.2. Accounting for the cumulative semantic and semantic blocking effects

In the literature, two computational models were published that explain cumulative semantic effects, namely the models of Howard et al. (2006) and Oppenheim et al. (2010). In addition, the model of Oppenheim et al. explains findings from blocked-cyclic naming, involving healthy participants as well as aphasic patients. Below, I briefly describe these models and indicate how they account for the semantic effects.

#### 2.2.1. The model of Howard et al.

The model of Howard et al. (2006) assumes that unitary concept nodes are linked to lexical nodes by excitatory feedforward-only connections. Lexical nodes are linked to each other by inhibitory connections. A picture (e.g., of a fork) activates the corresponding concept node (FORK) and partly the concept nodes of semantically related words (e.g., SPOON, GLASS, KNIFE, CUP), and activation spreads from concepts to lexical nodes. At each time step, the activation of every node is updated by a standard activation function. When the activation

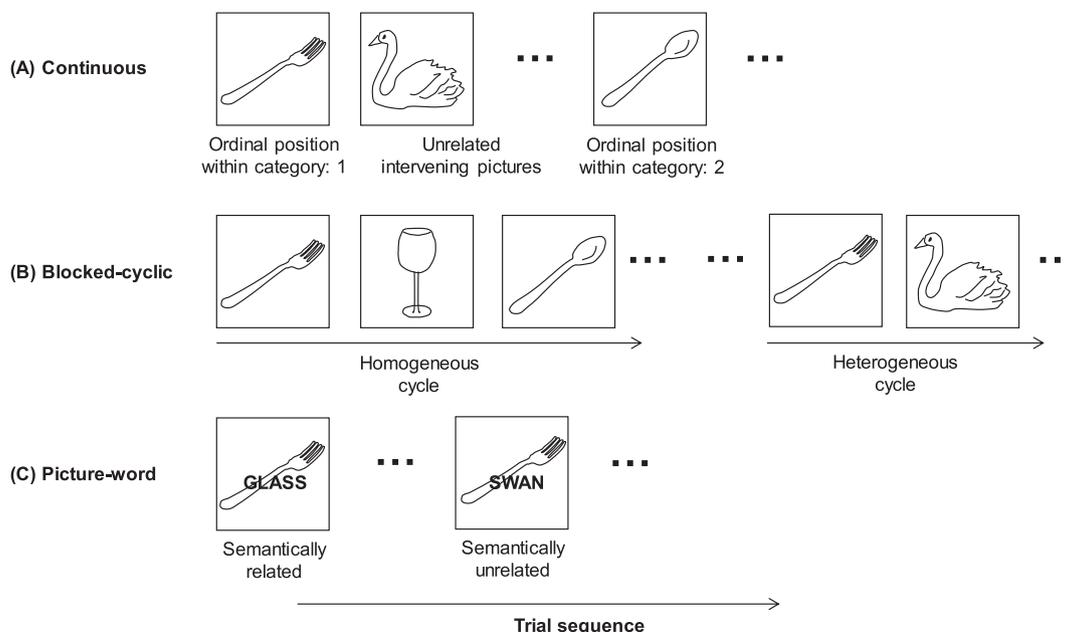


Fig. 1. Illustration of the trial sequence and conditions in the three paradigms: (A) continuous naming of pictures in different ordinal positions within a semantic category, here tableware, (B) blocked-cyclic naming of pictures within semantically homogeneous and heterogeneous cycles, and (C) naming pictures combined with semantically related or unrelated distractor words.

of a lexical node (*fork*) exceeds threshold, the node is selected, and the connection between the concept and the lexical node is strengthened (between FORK and *fork*). When later another picture from the same semantic category has to be named (e.g., a spoon), the lexical node of the previously named picture (*fork*) is activated more strongly because of the strengthened connection. As a consequence, the inhibition from this previously selected lexical item will be stronger, and the selection of the target (*spoon*) will be delayed (in terms of number of processing time steps required to reach the selection threshold). Inhibition will increase with the number of previously named pictures in a particular category, yielding cumulative semantic interference. Because the strengthening of connections is long-lasting, the interference is independent of the lag between pictures (but see Schnur, 2014).

By assuming the same connection strengthening in blocked-cyclic naming, the model would seem to be able to explain the semantic blocking effect, although this remains to be demonstrated by computer simulation. In the homogeneous condition, pictures from the same semantic category are named, which leads to long-term strengthening of the connections between concepts and lexical items within semantic categories, which increases inhibition and delays selection. However, this does not explain why no effect or semantic facilitation rather than interference is obtained during the first cycle and why the semantic effect is typically not cumulative in the blocked-cyclic paradigm.

### 2.2.2. The model of Oppenheim et al.

The model of Oppenheim et al. (2010) assumes that conceptual (semantic) feature nodes are linked to lexical nodes by excitatory and inhibitory feedforward-only connections. For example, conceptual features like MADE OF METAL and HAS TINES are linked by excitatory connections to the lexical node of *fork*, while some of these features (e.g., HAS TINES) have inhibitory connections to other lexical nodes (e.g., *spoon*). Before the model is applied to cumulative semantic and semantic blocking effects, the connection weights are set through a supervised competitive learning process. This pre-experimental learning process is thought to represent the acquisition of the production vocabulary (i.e., the mapping of concepts onto words). For each word (e.g., *fork*), the activation of the conceptual features (e.g., MADE OF METAL and HAS TINES) and the activation of the corresponding lexical node (*fork*) is set to 1 and the activation of all other words to 0.

Next, the activation of the lexical nodes is updated once via a logistic function, and the connection weights are changed such that the difference between the actual activation (a real-valued number) and the desired activation (0 or 1) is reduced for all words.

In simulating continuous or blocked-cyclic naming, the conceptual features for a picture (e.g., a fork) are activated, and the activation of all lexical nodes is updated once (via the logistic function) based on the feature activations. Next, the activation of each lexical node is multiplied by a constant boosting factor, until the activation of one of the nodes (e.g., *fork*) exceeds threshold and selection occurs. The selection threshold concerns either a critical difference in activation between this node and all other nodes (selection by competition) or concerns an absolute activation value regardless of the activation of the other nodes (noncompetitive selection). However, before boosting starts and a lexical node is selected (i.e., regardless of whether the selection is correct), connection weights are changed such that the difference between the actual activation and the desired activation is reduced for all lexical nodes. When later another picture from the same semantic category has to be named (e.g., a spoon), the lexical node of the previously named picture (*fork*) is activated more strongly and the lexical nodes of other category members (including the picture name *spoon*) are activated less strongly, which delays responding (in terms of number of boosts required to reach the selection threshold). Computer simulation by Oppenheim et al. (2010) of the experiment of Howard et al. (2006) showed that the delay in responding increases as a function of the number of previously named pictures in a particular category, yielding cumulative semantic interference. Because the strengthening and weakening of connections in the model is long-lasting, the interference effect is independent of the lag between pictures (but see Schnur, 2014).

Semantic interference in blocked-cyclic naming is explained along the same lines. Oppenheim et al. (2010) presented simulations of Experiment 1 of Schnur et al. (2006), who tested participants in semantically homogeneous and heterogeneous conditions, for four cycles each. The model yielded a semantic interference effect, which increased across cycles, as empirically observed by Schnur et al. However, the model does not explain why semantic facilitation was empirically obtained in the first cycle, and why the semantic effect is often not cumulative across cycles in other studies (see Belke & Stielow, 2013).

### 2.2.3. The need to account for semantic distractor effects

The models of Howard et al. (2006) and Oppenheim et al. (2010) were not applied to picture-word interference. Their accounts of cumulative semantic and semantic blocking effects assume an origin in the links between concepts and lexical items and a lexical locus. Elsewhere, Levelt et al. (1999) and Roelofs (1992, 2003) argued that semantic distractor effects in picture-word interference have a lexical locus too, which is supported by accumulating RT evidence (for reviews, e.g., Aristei & Abdel Rahman, 2013; Roelofs, Piai, & Schriefers, 2013; Starreveld, La Heij, & Verdonschot, 2013). This would imply that picture-word interference data are also relevant for the models of Howard et al. and Oppenheim et al. However, a number of researchers assume a locus of the semantic distractor effect in perceptual or conceptual processes (e.g., Dell'Acqua et al., 2007; Van Maanen et al., 2009) or in an articulatory buffering stage (Finkbeiner & Caramazza, 2006). If these researchers are right, a unified account of cumulative semantic, semantic blocking, and semantic distractor effects is not possible, and there would be no need to apply the models of Howard et al. and Oppenheim et al. to picture-word interference.

The next subsection reviews electrophysiological, hemodynamic, and patient evidence on continuous naming, blocked-cyclic naming, and picture-word interference. The evidence suggests that semantic effects in the three paradigms have a common locus in lexical selection.

### 2.3. Electrophysiological, hemodynamic, and patient evidence for a common lexical locus

Studies using electroencephalography (EEG) and magnetoencephalography (MEG) have provided evidence on the time windows of the semantic effects during picture naming in the continuous, blocked-cyclic, and picture-word interference paradigms. Fig. 2 shows the median onsets and offsets of the time windows in the electrophysiological studies (i.e., continuous: Costa et al., 2009; Rose & Abdel Rahman, 2017; blocked-cyclic: Aristei, Melinger, & Abdel Rahman, 2011; Janssen, Carreiras, & Barber, 2011; Janssen, Hernández-Cabrera, Van der Meij, & Barber, 2015; Maess, Friederici, Damian, Meyer, & Levelt, 2002; picture-word: Blackford, Holcomb, Grainger, & Kuperberg, 2012; Dell'Acqua et al., 2010; Piai, Roelofs, Jensen, Schoffelen, & Bonnefond, 2014; Piai, Roelofs, & Van der Meij, 2012; Zhu, Damian, & Zhang, 2015). Only studies that obtained semantic effects and measured naming RTs are included (for some studies, the mean RT was not given numerically but had to be derived from the

graphs).

The different views on the locus of the semantic distractor effect (i.e., perceptual and conceptual encoding, lexical selection, or articulatory buffering) predict different time windows for the effect. In a meta-analysis of word production studies, Indefrey and Levelt (2004; Indefrey, 2011) estimated that perceptual and conceptual encoding are completed around 200 ms after picture onset (in line with much evidence that a picture is conceptually identified within 200 ms, see DiCarlo, Zoccolan, & Rust, 2012). Lexical selection starts at about 200 ms and lasts until about 275 ms, followed by word-form encoding, while articulatory buffering starts no earlier than after approximately 455 ms. This is the estimated onset of phonetic encoding, where articulatory programs are encoded, which then may be buffered. Fig. 2 shows that in all three naming paradigms, there is overlap between the time windows of the electrophysiological effects and lexical selection. The electrophysiological effects occur later than perceptual and conceptual encoding (i.e., later than 200 ms) in all three paradigms. Also, the semantic effect in picture-word interference occurs earlier than articulatory buffering (i.e., earlier than 455 ms).

One caveat is that the stage estimates of Indefrey and Levelt (2004; Indefrey, 2011) hold for a mean naming RT of 600 ms, whereas the median RTs in Fig. 2 ranged between 688 and 897 ms. Clearly, if the RT is 897 ms, speakers do not complete all stages of naming within 600 ms and then wait for 297 ms to initiate articulation. Thus, the estimates need to be rescaled if the mean RT is shorter or longer than 600 ms.

The two most straightforward options for rescaling are proportional and informed procedures (Indefrey, 2011; Roelofs & Shitova, 2017). In proportional rescaling, the onset and offset estimates for the stages are increased or decreased in proportion to the extent that the observed mean RT was longer or shorter than 600 ms. In the informed procedure, rescaling is based on specific knowledge about the factors that caused the mean RT to be longer or shorter than 600 ms. Based on electrophysiological evidence, Laganaro, Valente, and Perret (2012) argued that individual differences in naming RT are for the most part due to differences in lexical selection duration. Accordingly, the informed procedure adds the difference between the observed mean RT and 600 ms to the offset estimate for lexical selection.

Fig. 2 also shows the estimated time windows for lexical selection in the three naming paradigms under proportional and informed rescaling. For picture-word interference, the estimated onset of phonetic encoding (based on Indefrey, 2011; Indefrey & Levelt, 2004) is indicated for evaluating the proposal that semantic effects arise during articulatory buffering (Finkbeiner & Caramazza, 2006). The estimated onset of phonetic encoding corresponds well with the event-related brain potential (ERP) evidence of Bürki, Pellet, and Laganaro (2015) that suggests access to articulatory programs around 150–180 ms before articulation onset. The figure shows that there is considerable overlap between the estimated time windows of the electrophysiological effects of semantic relatedness and lexical selection in all three paradigms regardless of type of scaling. The electrophysiological effects occur later than perceptual and conceptual encoding and much earlier than articulatory buffering. These results suggest that the semantic effects in the three paradigms share a lexical selection locus.

In an MEG study, Maess et al. (2002) not only obtained evidence on the time window of the semantic blocking effect but also its locus in the brain, namely the middle part of the left middle temporal gyrus (MTG). More recently, Piai et al. (2014) obtained evidence in an MEG study that the semantic distractor effect in picture-word interference also occurs in this area. Using perfusion functional magnetic resonance imaging (fMRI), de Zubicaray, McMahon, and Howard (2015) observed a cumulative semantic effect in left middle MTG, and de Zubicaray, Johnson, Howard, and McMahon (2014) observed a semantic blocking effect in this area. Thus, the semantic effects in the three paradigms also seem to share a neuroanatomical locus, namely the left middle MTG. In their meta-analysis of neuroimaging studies of spoken word production, Indefrey and Levelt (2004; Indefrey, 2011) associated this area with

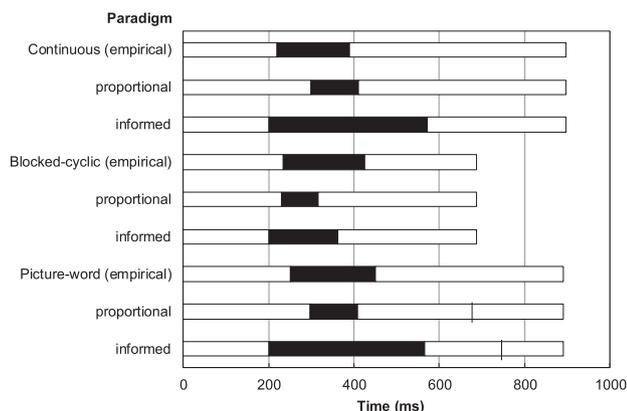


Fig. 2. Time windows of the semantic effects (black horizontal bars) in electrophysiological studies on picture naming using continuous, blocked-cyclic, and picture-word interference paradigms. The empirical windows concern the median onset and offset times of the effects plotted within the median response time (white horizontal bars). For each paradigm, the estimated time windows of lexical selection under proportional and informed rescaling are shown. For picture-word interference, the estimated onset of phonetic encoding (after which articulatory buffering may happen) is indicated (small vertical black lines).

lexical selection.

In a voxel-based lesion-deficit analysis of semantic errors in picture naming by speakers with aphasia, [Schwartz et al. \(2009\)](#) observed that semantic error rate is most highly associated with damage to the middle section of the left MTG (see also [Walker et al., 2011](#)). Also, [Harvey and Schnur \(2015\)](#) observed that the amount of damage to the mid to posterior left MTG correlated with the number of errors in blocked-cyclic naming. Using picture-word interference, [Piai and Knight \(2017\)](#) observed that patients with left-temporal damage showed an increased semantic interference effect in the error rates relative to healthy controls. In an EEG study, [Laganaro et al. \(2009\)](#) recorded ERPs during picture naming by six aphasic speakers and a group of healthy controls. Two patients produced many semantic errors in spontaneous speech and picture naming. These patients showed divergent ERPs between 110 and 430 ms after picture onset, as revealed by waveform and topographic map analysis. This time window overlaps with that of lexical selection. Thus, the patient studies provide converging evidence for the association of semantic effects in picture naming with lexical selection.

The overlapping time windows of the semantic effects in the three paradigms, the common neuroanatomical locus, and the patient data support a unified account of the semantic effects rather than accounts that assume different loci. For example, [Navarrette et al. \(2014\)](#) proposed a lexical locus for semantic interference in blocked-cyclic naming, but a locus in articulatory buffering for semantic interference in the picture-word paradigm. For the latter, other researchers have proposed a locus in the perceptual or conceptual encoding of the picture ([Dell'Acqua et al., 2007](#); [Van Maanen et al., 2009](#)). However, the electrophysiological, hemodynamic, and patient evidence supports the assumption of a locus in lexical selection in all three paradigms. In the next section, the WEAVER++ model is outlined, which assumes such a common lexical locus.

### 3. Model and computer simulations

Conversations are usually about specific topics, such as a dinner or a wedding. Speakers and listeners often repeatedly retrieve exemplars of a semantic category (e.g., tableware: fork, spoon, glass, cup, knife) or thematic associates (e.g., wedding: church, wedding dress, ring, cake, bouquet). Conversational partners establish temporary agreements about how objects are to be conceptualized (e.g., [Brennan & Clark, 1996](#)). The concepts that are introduced early in a discourse remain reference points for later contributions to a conversation (e.g., [Gee & Handford, 2012](#); see [Kemmerer, 2015](#), for a review of the cognitive neuroscience evidence on discourse). Therefore, it seems useful for the language system to temporarily heighten the accessibility of lexical concepts after their selection. This way, conceptual information related to the topic of the conversation remains readily available for both speakers and listeners for a short period of time (e.g., [Levelt, 1989](#)). However, the heightened availability may come with a small price for other related concepts that have not yet been retrieved, as the findings on cumulative semantic interference suggest ([Hoedemaker, Ernst, Meyer, & Belke, 2017](#)).

To account for cumulative semantic and semantic blocking effects, I propose here that heightened availability after selection of a lexical concept creates a bias towards the concept in the subsequent processing of another lexical concept within the same semantic category or thematic context. For example, naming a picture (e.g., of a fork) results in a bias towards the concept linked with the picture (FORK) in the subsequent naming of a semantically related picture (e.g., of a spoon). An account in terms of a temporary conceptual bias readily explains a number of empirical findings that seem to be more difficult to explain by existing accounts in terms of long-lasting learning of conceptual-lexical connection weights ([Howard et al., 2006](#); [Oppenheim et al., 2010](#)). These findings include transfer of interference from listening to picture naming and the absence of cumulative interference with lags larger than eight. The remainder of this section explains how the

conceptual bias has been implemented in the WEAVER++ model. The next section (Section 4) reports the results of computer simulations that examined whether the inclusion of conceptual bias in the model is sufficient for an account of cumulative semantic and semantic blocking effects while preserving the model's account of semantic distractor effects.

The WEAVER++ model makes a distinction between a declarative lexical network and a procedural rule system (see [Eichenbaum, 2012](#), for a review of the cognitive neuroscience evidence for distinct declarative and procedural memory systems in the brain). The declarative network contains nodes for concepts, lemmas, morphemes, phonemes, and syllable motor programs. Lexical selection in the model consists of the selection of lemmas. Lemmas specify the grammatical properties of words, such as grammatical category (e.g., noun, verb) and grammatical gender (in case of nouns) for several languages, including German and Dutch. Lemmas were localized to the middle part of the left MTG in the extensive meta-analysis of neuroimaging studies performed by [Indefrey and Levelt \(2004; Indefrey, 2011\)](#), for which there is converging evidence from lesion-deficit analyses in aphasia (e.g., [Schwartz et al., 2009](#); [Walker et al., 2011](#)), as indicated earlier.

The model assumes that the lexical network is accessed by spreading activation. Activation spreads continuously from level to level (i.e., from lexical concepts via lemmas, morphemes, and phonemes to syllable motor programs), whereby each node sends a proportion of its activation to connected nodes. Procedural if-then rules select activated nodes from the network depending on the task demands specified in working memory (e.g., to name a picture or word). After a lexical concept is selected for a picture, an if-then rule enhances the concept's activation to achieve speeded and accurate lemma selection. The top-down enhancement is provided until a lemma is selected. To be selected, the activation of a lemma node has to exceed the activation of other lemmas by a critical amount, which is the lexical selection threshold. The actual moment of selection of the lemma node is then a random event, whose probability is determined by a ratio of the activation of the lemma and the other lemmas belonging to the same semantic category or theme. To account for semantic effects, the conceptual and lemma levels are relevant. Therefore, word-form encoding in the model is not discussed here, and it was also not included in the present simulations.

In the continuous naming studies of [Howard et al. \(2006\)](#), [Belke \(2013\)](#), and others, the critical pictures were drawn from 24 semantic categories with five exemplars each (e.g., fork, spoon, glass, cup, knife). Pictures were presented to participants without repeating any item. Performance was assessed as a function of the number of previously named pictures in a category. Belke used these pictures to examine picture naming and picture classification, and the corresponding written words were used to examine word naming and word naming with a gender-marked determiner in German. Picture classification concerned classifying the pictures as man-made or natural by pressing one of two buttons. For example, in categorizing a picture of a fork, the participants pressed the button for “man-made” rather than the button for “natural”. Word naming with a gender-marked determiner in German concerned responding to a written word by saying the word preceded by its gender-marked definitive article. For example, in response to the written word *Gabel*, participants said “die Gabel” (i.e., with the article “die” rather than “der” or “das” because the word *Gabel* has feminine grammatical gender).

To be able to simulate performance on these tasks, a semantic category was represented by a network of five exemplars, one for each ordinal position, as shown in [Fig. 3](#) for German (the language in Belke's experiments). Connections between lexical concepts and between lexical concepts and lemmas are bidirectional. Lexical concept nodes (e.g., FORK) are assumed to be connected to nodes for conceptual features (e.g., MADE OF METAL, HAS TINES, etc.), which are not shown in the figure. Conceptual features were also not included in the simulations to simplify matters. According to the model, nodes for lexical concepts

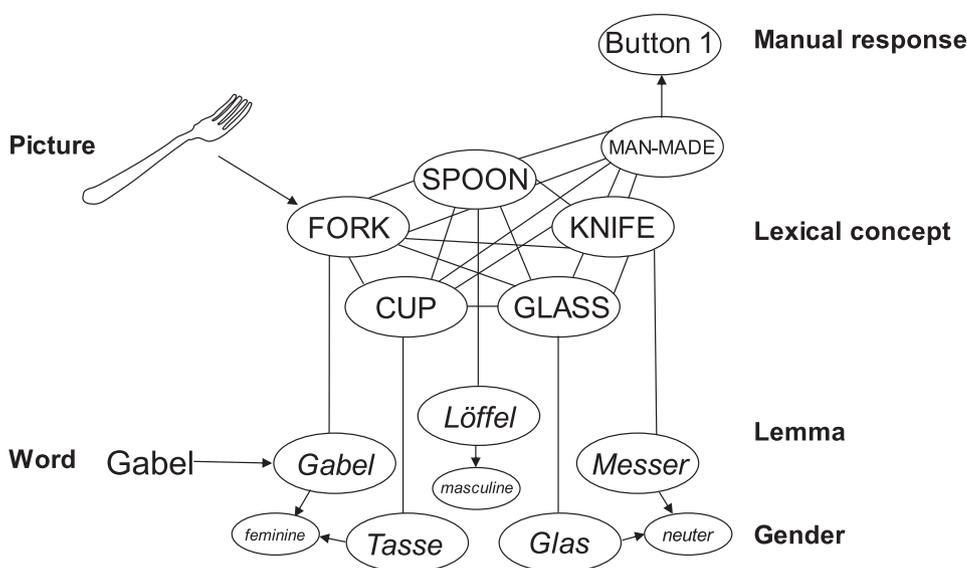


Fig. 3. Illustration of the representation of a semantic category (tableware) for German in the WEAVER++ model. See text for explanation.

rather than for conceptual features (except for visual ones) play a necessary role in lexical selection for picture naming (see Roelofs, 1992, 1997b, for a theoretical motivation, and Abdel Rahman, van Turenout, & Levelt, 2003, for empirical evidence).

Activation spreads through the network according to a linear function with a decay factor:

$$a(m, t + \Delta t) = a(m, t)(1-d) + \sum_n ra(n, t) + bias(m)$$

The term  $a(m, t)$  is the activation level of node  $m$  at point in time  $t$ ,  $d$  is a decay rate, and  $\Delta t$  is the duration of a time step in ms. The middle term with the summation denotes the amount of activation that  $m$  receives between  $t$  and  $t + \Delta t$ , where  $a(n, t)$  is the output of neighbor  $n$  (equal to its level of activation). The rightmost  $bias(m)$  term is a new addition to the model (i.e., it was not part of previous simulations with the model). Bias terms are widely used in connectionist networks (e.g., McClelland & Rumelhart, 1986). The parameter values (i.e.,  $d$ ,  $r$ , and  $\Delta t$ ) were the same as in earlier WEAVER++ simulations (e.g., Levelt et al., 1999; Piai et al., 2014; Roelofs, 1992, 1997a, 2003, 2004, 2007, 2008a, 2008b, 2014; Roelofs & Hagoort, 2002; Roelofs, Van Turenout, & Coles, 2006). The lexical selection threshold (and the button selection threshold in manual responding) was set to 1.6 in all simulations.

As indicated, a key assumption is that selection of a lexical concept creates a bias towards the concept in the subsequent processing of other lexical concepts within the same semantic domain. To simulate this effect, a bias term was added to each lexical concept node in the model. After each trial on which a lexical concept node was selected, the bias term increased by a constant value, arbitrarily set to 2.5. The biases are assumed to be relatively durable but return to zero when the number of intervening unrelated pictures between category exemplars is constantly larger than eight (Schnur, 2014). That is, the heightened availability of lexical concepts needs to be maintained by reactivating the semantic domain in time.

In the simulations of picture naming and picture classification, a picture activated the corresponding lexical concept node (e.g., a picture of a fork activated the lexical concept FORK) followed by a spread of activation through the network. In word naming and word naming with a gender-marked determiner, a written word activated the corresponding lemma node (e.g., the word *Gabel* activated the lemma of *Gabel*) followed by spreading activation. In all naming tasks (i.e., picture naming, word naming, and word naming with a gender-marked determiner), a lemma node was selected when its activation exceeded the activation of other lemmas by a critical amount, after which the actual moment of selection was determined by the ratio of the activation of the target versus the competitors within a semantic category or

theme. Word naming with a gender-marked determiner additionally involved selection of a grammatical gender node (i.e., feminine, masculine, or neuter) when its activation exceeded the selection threshold (taken as an absolute activation value). In picture classification with manual responding, a button node (man-made vs. natural) rather than a lemma node was selected when its activation exceeded the selection threshold.

The WEAVER++ simulations were computationally implemented using the C programming language and the programming environment of Microsoft Visual C++ 2017. The source code of the simulation program is available from the archive of the Open Science Framework (osf.io/6ysp2) or from the author.

## 4. Results and discussion

### 4.1. Cumulative semantic effects

The simulations of performance in the continuous paradigm examined categorical effects in picture naming, picture classification, word naming, and word naming with a gender-marked determiner in German. Also, the model was applied to thematic relations, transfer between listening and picture naming, and transfer between picture and word naming tasks. Furthermore, simulations addressed neuroimaging evidence.

#### 4.1.1. Categorical effects in picture naming, picture classification, and word naming tasks

As a starting point, I conducted simulations for the study of Belke (2013), in which the continuous paradigm was used to examine picture naming, picture classification, word naming, and word naming with a gender-marked determiner in German. For example, in response to a picture of a fork, participants said “Gabel” (picture naming) or they pressed a button for a “man-made” response (picture classification), and in response to the written word *Gabel*, they said “Gabel” (word naming) or they said “die Gabel” (word naming with a gender-marked determiner).

Fig. 4 shows the simulation results together with the real data for picture naming and picture classification. Ordinal position effects were obtained for these tasks in the simulations. The simulation of picture naming yielded cumulative semantic interference, as empirically observed (Belke, 2013; Howard et al., 2006). In contrast, the simulation of picture classification yielded cumulative semantic facilitation, as empirically observed by Belke.

The picture naming RT for the first ordinal position was about

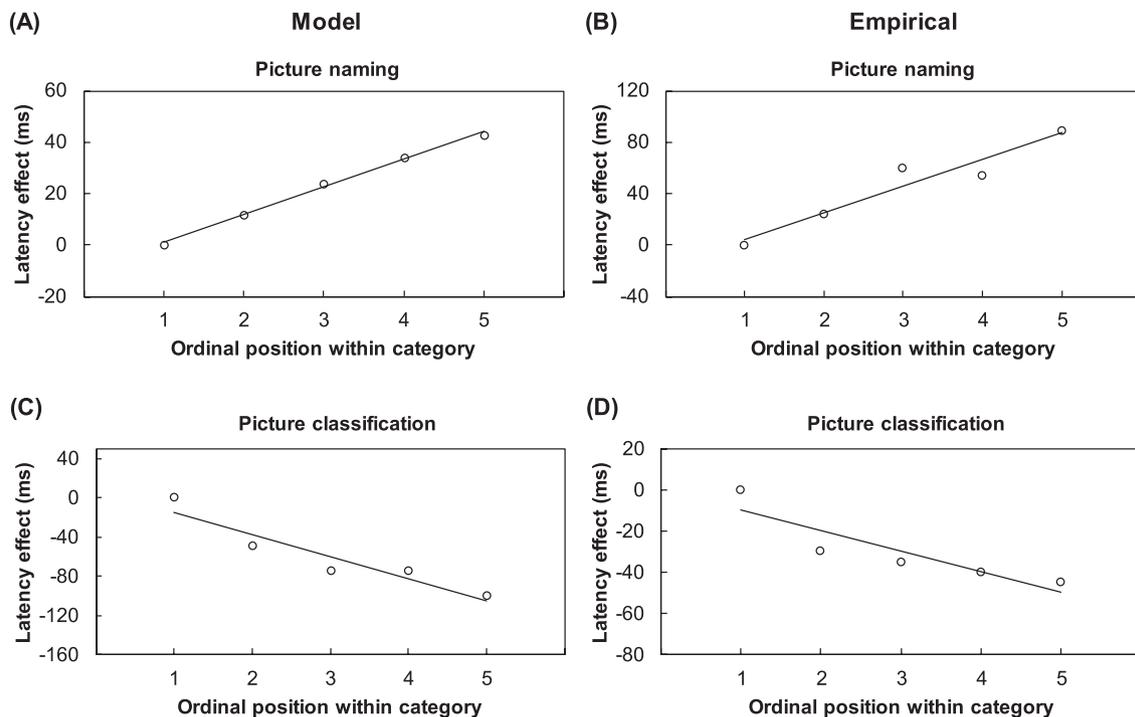


Fig. 4. Behavioral latency results in the continuous paradigm for picture naming and picture classification: (A, C) simulation results and (B, D) empirical observations by Belke (2013, Experiment 1). The latency effect concerns the difference between the first position and the later ones. Linear trend lines are added.

760 ms in the study of Belke (2013, Experiment 1). Under proportional rescaling of the lexical selection time of 75 ms estimated by Indefrey and Levelt (2004; Indefrey, 2011), lexical selection is estimated to take 95 ms. In the WEAVER++ simulation, the lexical selection time was 81 ms for the first ordinal position, which is close to the estimate from the empirical naming RT.

Riley, McMahon, and de Zubicaray (2015) observed that the cumulative semantic facilitation in RTs is also obtained when the participants semantically classify the pictures by saying “living” or “non-living” rather than by pressing buttons. Thus, cumulative semantic facilitation in picture classification occurs regardless of whether participants respond manually (Belke, 2013) or vocally (Riley et al.).

How does the model explain the cumulative semantic interference and facilitation effects? In picture naming, the lexical concepts of the different exemplars of a semantic category (e.g., fork, spoon, glass, cup, knife) are mapped onto different lemma responses (*Gabel, Löffel, Glas, Tasse, Messer*), which compete for selection. Because of this *divergent mapping*, a conceptual bias for previously named pictures in the category will yield semantic interference, which increases as a function of the number of previously named category exemplars. In contrast, in picture classification, the lexical concepts of the different exemplars of a semantic category are mapped onto the same response (e.g., fork, spoon, glass, cup, knife, are mapped onto the button response for “man-made” or the corresponding vocal response). Because of this *convergent mapping*, a conceptual bias for previously classified pictures in the category will yield semantic facilitation, which increases as a function of the number of previously classified category exemplars. Because the conceptual bias is durable to some extent (up to a lag of eight intervening unrelated pictures), the interference and facilitation effects will be independent of the exact lag between semantically related pictures, as empirically observed.

The goal of the simulations was to examine whether the model accounts for the data patterns rather than seeking a quantitative fit. Therefore, I ran all simulations with a single set of fixed parameter values rather than fine-tuning the parameter values to optimize the fits. As Fig. 4 shows, the increase in latency per ordinal position in picture naming is smaller in the simulations (i.e., about 11 ms) than in the

empirical data (about 21 ms) that Belke (2013) obtained. The increase in Belke and Stielow (2013) and Costa et al. (2009) was about 12 ms, in Navarrette et al. (2010) and Schnur (2014) it was about 14 ms, and in Howard et al. (2006) it was about 30 ms. By raising the lexical selection threshold in the model, the increase also becomes larger, and the model quantitatively fits the larger empirical effects. The decrease in latency per ordinal position in picture classification was larger in the simulations than in the empirical data of Belke. By lowering the selection threshold for button-node selection (for the manual response) in the model, the latency decrease becomes smaller, and the model quantitatively fits the empirical data.

In addition, I ran simulations for word naming and word naming with a gender-marked determiner. For these tasks, the model yielded no ordinal position effects, which corresponds to the empirical findings of Belke (2013). Navarrette et al. (2010) also obtained no ordinal position effects for word naming with a gender-marked determiner in German and Italian. According to the model, word naming can be achieved without selection of a lexical concept, by directly mapping an orthographic form onto an output phonological form or by selecting a lemma and mapping it onto an output phonological form. Because a lexical concept is not selected, the bias term will stay at zero. Consequently, conceptual bias will not occur, and ordinal position effects will not be obtained. Similarly, in word naming with a gender-marked determiner, a lemma needs to be selected to identify the grammatical gender (see Fig. 3), but concept selection is not needed. Thus, again, because a lexical concept is not selected, conceptual bias will not occur, and ordinal position effects will be absent.

Interestingly, Navarrete, Caccaro, Pavani, Mahon, and Peressotti (2015) also observed cumulative semantic interference when deaf participants named pictures by producing the corresponding sign, but there was no effect when the sign was produced in response to written words. This suggests that naming pictures by producing signs is conceptually driven, like vocally naming pictures, whereas naming words by producing signs can be done without selecting a lexical concept, just like vocally naming words.

Rose and Abdel Rahman (2017) observed that greater overlap in conceptual features among concepts within a semantic category

increases the cumulative semantic interference effect in picture naming RTs. Moreover, in a further analysis of the empirical data of Howard et al. (2006), Alario and Moscoso del Prado Martín (2010) observed that conceptual feature overlap modulated naming performance. The WEAVER++ model assumes that lexical concepts are connected to their conceptual features (e.g., Roelofs, 1992, 1997b), in line with Belke (2013), Lambon Ralph (2014), Patterson, Nestor, and Rogers (2007), Vigliocco, Vinson, Lewis, and Garret (2004), and others. Reverberation of activation via shared conceptual features may affect the impact of conceptual bias, which may explain the empirical observations on the influence of feature overlap. It should be noted that the effect of high versus low feature overlap in other picture naming paradigms, such as picture-word interference, is far from resolved (e.g., Hutson & Damian, 2014, found no clear relationship between conceptual overlap and the size of the semantic effect). More research is needed to assess the influence of the degree of conceptual feature overlap in the three paradigms.

Cumulative semantic interference is obtained for lags 2–8 between category exemplars and the effect does not vary with the exact lag (Howard et al., 2006). However, Schnur (2014) observed that cumulative semantic interference disappears when the lag is consistently 8–14 or 20–50 intervening unrelated pictures. Still, the interference effect remains with lags 8–14 when lags of two also occur in the experiment. In terms of the WEAVER++ model, this suggests that experience with short lags diminishes the decay of the conceptual biases in an experiment. Oppenheim et al. (2010) assume that competitive learning during an experiment is a continuation of the pre-experimental learning by which the connections weights were acquired to map conceptual features onto corresponding lexical items. However, the findings of Schnur suggest that effects of learning within an experiment disappear with lags consistently larger than eight, which seems to challenge the learning assumptions of Oppenheim et al. That is, the pre-experimental learning of connection weights would require that category exemplars are named with less than eight intervening unrelated naming occurrences, which is not how children learn their vocabularies. Perhaps the model of Oppenheim et al. may explain the observations of Schnur by assuming a different type of learning during an experiment than before the experiment. It may be assumed that whereas the pre-experimental learning of connection weights is long-lasting, during an experiment a type of soft learning of connection weights occurs that disappears when lags are consistently larger than eight, except when shorter lags have been experienced in the experiment. Future simulations may examine the utility of this idea.

The competitive learning in the model of Oppenheim et al. (2010) yields both repetition priming effects in blocked-cyclic naming (i.e., RT decreases across cycles) and semantic interference in blocked-cyclic and continuous naming. However, Hughes and Schnur (2017) obtained evidence that repetition priming and semantic interference effects are not related, which suggests different origins of the effects. In line with this evidence, conceptual bias in WEAVER++ yields cumulative semantic interference but little or no repetition priming (the latter may

result from repeated access to perceptual, conceptual, lemma, and form representations, yielding long-term changes that are outside the scope of the present article).

#### 4.1.2. Effects from thematic associations

Rose and Abdel Rahman (2016) reported three experiments showing that cumulative semantic interference is also obtained when pictures are related by a common theme (for thematic interference in blocked-cyclic naming, see Abdel Rahman & Melinger, 2007). For example, a church, ring, cake, wedding dress, and bouquet are all belonging to the theme of a wedding. In the first experiment of Rose and Abdel Rahman, the themes and associated concepts were pre-activated before the experiment by giving participants a free association task in which they had to name all objects associated with the different themes. In the second experiment, there was no such free association task, and in the third experiment, the stimulus set was constructed such that any categorical relation among the theme associates was absent. In all three experiments, the picture naming RT for the thematic associates increased linearly with ordinal position, that is, linearly as a function of the number of previously named pictures associated with the same theme. The effect was independent of the lag (2–8) between the thematically associated pictures. These findings indicate that a categorical relationship is not necessary for cumulative semantic interference to occur in picture naming.

It is thought that conceptual memory represents thematic information differently from categorical information (e.g., de Zubicaray, Hansen, & McMahon, 2013; Rose & Abdel Rahman, 2016; Schwartz et al., 2011). Rose and Abdel Rahman examined cumulative semantic interference in naming thematically related pictures using critical pictures from 16 different themes with five associates each (e.g., wedding: church, ring, cake, wedding dress, bouquet; holidays: beach, plane, sun blocker, suitcase, bikini) in German. To be able to simulate performance in these experiments, a thematic context was represented by a network of five lexical concepts (e.g., CHURCH, RING, CAKE, WEDDING DRESS, BOUQUET), one for each ordinal position. There were no connections among the concept nodes except that they were all linked to a common node representing the associated theme (e.g., WEDDING). The lexical concepts were linked to the lemmas of the corresponding German words (i.e., Kirche, Ring, Torte, Brautkleid, Blumenstraus). In the simulations, there was no pre-activation of thematic associations and categorical relations were absent, corresponding to the third experiment of Rose and Abdel Rahman.

Fig. 5 shows the simulation results together with the real data. The simulation yielded an ordinal position effect, as empirically observed. Thus, for cumulative semantic interference to occur in the model, it is sufficient that each newly named picture belongs to a shared theme (e.g., wedding) while categorical relations are absent. This corresponds to the empirical findings of Rose and Abdel Rahman (2016).

Cumulative semantic interference arises in the model of Oppenheim et al. (2010) because of conceptual feature overlap (e.g., spoon and fork share conceptual features such as MADE OF METAL). Such overlap

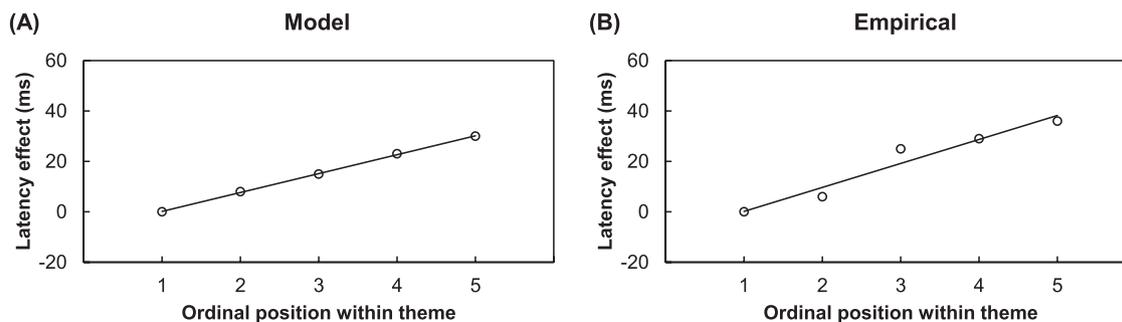


Fig. 5. Behavioral latency results in the continuous paradigm for thematic associations: (A) simulation results and (B) empirical observations by Rose and Abdel Rahman (2016, Experiment 3). The latency effect concerns the difference between the first position and the later ones. Linear trend lines are added.

exists in case of categorical relationships. One might argue that pictures related by a common theme share thematic features (e.g., ring and cake share the feature OCCURS AT A WEDDING). As a consequence, cumulative semantic interference in picture naming may possibly occur for thematic relations in this model. Howard et al. (2006) demonstrated that their model accounts for cumulative semantic interference in picture naming regardless of whether or not there is feature overlap, as long as related unitary concept nodes share activation. Thus, cumulative interference from thematic associations may occur if thematically associated unitary concepts share activation.

#### 4.1.3. Transfer of cumulative semantic effects

A temporary heightening of the availability of selected lexical concepts may be useful for speakers as well as listeners in a conversation. Using the continuous paradigm, Hoedemaker et al. (2017) observed that the cumulative semantic interference effect from categorical relatedness transfers from listening to picture naming when two speakers name pictures in different turns. On turn 1, one speaker names a picture while the other listens, and vice versa on turn 2, for two rounds. Importantly, cumulative semantic interference was obtained regardless of whether the listener actually saw the named picture or not.

According to WEAVER++, when listeners select a concept for the word that they hear (i.e., the picture naming response of the other participant), then the bias term for that concept will increase (just as it does in really naming the picture). As a consequence, there will be a conceptual bias towards that concept in the subsequent naming of a picture from the same category. In the simulation of a listening trial, a spoken word activated the corresponding lemma (see Fig. 3), and subsequently the corresponding lexical concept, which was selected. This selection created a bias toward the concept in the subsequent processing of other lexical concepts within the same semantic domain (i.e., during a naming trial). As a consequence, semantic interference was transferred from listening to picture naming. Fig. 6 shows the simulation results together with the real data. The model captures the data.

The data challenge the models of Howard et al. (2006) and Oppenheim et al. (2010), which are feedforward-only models assuming that cumulative semantic interference arises from picture naming. Perhaps these models may account for transfer of cumulative semantic interference by assuming that participants on non-naming trials covertly name the pictures. In line with this, Kuhlen and Abdel Rahman (2017) observed that transfer of cumulative semantic interference is obtained even when participants only believe that their partner is naming the picture, without actually hearing the partner. However, covert naming does not explain why the transfer is also obtained when listeners hear the names but do not see the pictures (Hoedemaker et al., 2017). To account for this effect, it has to be assumed that listeners conceptually identify the heard picture names and then covertly generate the corresponding name from the concepts. However, the models of Howard et al. and Oppenheim et al. lack mechanisms for speech

comprehension (i.e., they only have feedforward connections from concepts to lexical items).

Transfer of cumulative semantic interference also occurs from one language to another, as observed by Runnqvist, Strijkers, Alario, and Costa (2012). The WEAVER++ model accounts for this finding, because it assumes that lexical concepts are shared between the languages of a bilingual speaker (e.g., Roelofs, 2003; Roelofs, Dijkstra, & Gerakaki, 2013; Roelofs, Piai, Garrido Rodriguez, & Chwilla, 2016). Runnqvist et al. argued that transfer between languages challenges models in which competition occurs within but not between languages, like WEAVER++. However, if lexical concepts are shared between languages, and conceptual bias underlies the cumulative interference, then cross-language cumulative semantic interference may occur even when competition occurs within a language only (see Roelofs et al., 2016, for relevant WEAVER++ simulations).

Navarrete, Mahon, and Caramazza (2010) observed that picture naming with a gender-marked determiner induced cumulative semantic interference for subsequently naming words with a gender-marked determiner (in Italian), but there was no interference in the reverse order. The transfer effects from picture naming to word naming were about 13 ms and 20 ms for respectively the third and fourth ordinal positions within a semantic category. However, Belke (2013) could not replicate the transfer of cumulative semantic interference from picture naming with a gender-marked determiner to the naming of words with a gender-marked determiner (in German). Still, Navarrete, Mahon, Lorenzoni, and Peressotti (2016) replicated the findings of Navarrete et al. in a new study (in Italian): There was transfer of cumulative semantic interference from pictures to words.

According to Navarrete et al. (2010, 2016), the transfer of semantic interference from picture naming to word naming suggests that competitive learning as proposed by Oppenheim et al. (2010) happens for picture naming but not for word naming. That is, picture naming is conceptually driven, and therefore the strength of the connections between conceptual features and lexical items will be adjusted after naming a picture. In contrast, word naming with a gender-marked determiner is not conceptually driven, and therefore the strength of the connections is not modified. As a consequence, word naming will not yield a cumulative semantic effect and there will be no transfer. In contrast, picture naming yields cumulative semantic interference, and this effect may therefore transfer to word naming with a gender-marked determiner. The WEAVER++ model explains the transfer along similar lines. Word naming with a gender-marked determiner may proceed via the lemma level (see Fig. 3) without selecting a lexical concept, and thus creates no conceptual bias. However, picture naming requires lexical concept selection and creates conceptual bias, which may transfer to word naming with a gender-marked determiner, as simulations confirmed. The transfer effects from picture naming to word naming were 7 ms and 11 ms for respectively the third and fourth ordinal positions within a semantic category.

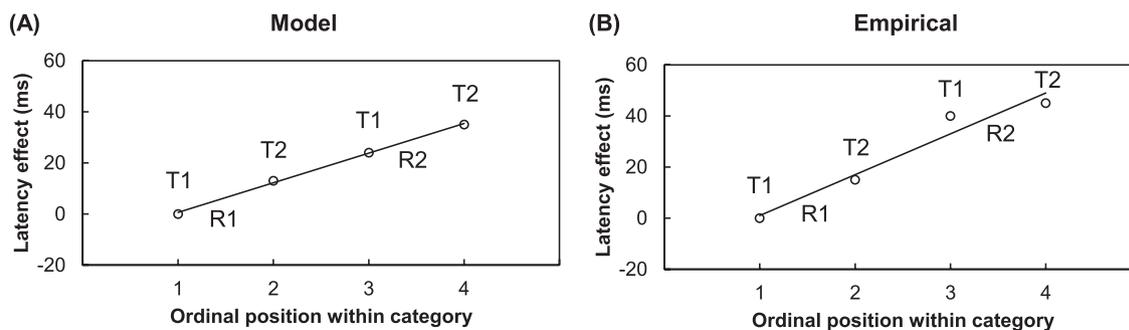


Fig. 6. Behavioral latency results in the continuous paradigm for turn 1 (T1) and turn 2 (T2) in round 1 (R1) and round 2 (R2): (A) simulation results and (B) empirical observations by Hoedemaker et al. (2017). The latency effect concerns the difference between the first position and the later ones. Linear trend lines are added.

#### 4.1.4. Effects in brain activity

In an fMRI experiment, [Canini et al. \(2016\)](#) observed that the blood-oxygen-level-dependent (BOLD) response in the left inferior frontal gyrus (LIFG) increases linearly with ordinal position in the continuous naming paradigm. The WEAVER++ model may account for this observation under the assumptions that top-down enhancement of the activation of lexical concepts in continuous naming is co-issued from LIFG (cf. [Roelofs, 2014](#)) and that the magnitude of the BOLD response reflects the duration of the enhancement in picture naming. The latter assumption has also been made by [Roelofs and Hagoort \(2002\)](#) and [Roelofs et al. \(2006\)](#) for enhancement of the activation of lexical concepts issued by the anterior cingulate cortex (ACC) during the performance of Stroop-like tasks (like picture-word interference), which was tested in WEAVER++ simulations. Evidence on ACC activity in picture-word interference comes from fMRI studies on picture naming by [de Zubicaray, Wilson, McMahon, and Muthiah \(2001\)](#) and by [Piai, Roelofs, Acheson, and Takashima \(2013\)](#), and from an MEG study of picture-word interference by [Piai et al. \(2014\)](#). In line with the findings of [Canini et al.](#) on the cumulative semantic effect in picture naming, [Schnur et al. \(2009\)](#) observed a semantic blocking effect on the BOLD response in the LIFG. In the WEAVER++ model, the top-down enhancement lasts until a lemma is selected. In the simulation of the experiment of the [Canini et al.](#), the BOLD response was assumed to be linearly related to the enhancement duration, with the intercept and slope of the response estimated from the empirical data. [Fig. 7](#) shows that the model captures the empirical data from [Canini et al.](#) on LIFG activity.

[Oppenheim et al. \(2010\)](#) tentatively associated the boost operation in their model with the LIFG. By assuming that the BOLD response in the LIFG reflects the number of boosts required for the different ordinal positions within a category, the model would seem to be able to account for the observations of [Canini et al. \(2016\)](#). However, in the model of [Howard et al. \(2006\)](#), top-down control plays no role, so it is unclear how this model accounts for the empirical observations on LIFG activity.

[de Zubicaray et al. \(2015\)](#) report on an perfusion fMRI study of picture naming in the continuous paradigm. They observed that activity in left middle MTG (which is thought to represent lemmas) increased with ordinal position within a category. Also, the LIFG was more active for later (i.e., the fourth and fifth position) than for earlier ordinal positions (i.e., the first to third position) but there was no linear increase of activity with position, which is different from what [Canini et al. \(2016\)](#) observed. In WEAVER++, the top-down enhancements are finely tuned to the duration of lemma selection. That is, the enhancement lasts until a lemma is selected, which explains the linear increase of LIFG activity observed by [Canini et al.](#) However, the observations of [de Zubicaray et al.](#) suggest that participants may also use a constant enhancement duration and increase this duration only once over the different ordinal positions. Simulations revealed that with such suboptimal enhancements in the model, cumulative semantic interference in the RTs is still obtained, even though LIFG activity would not

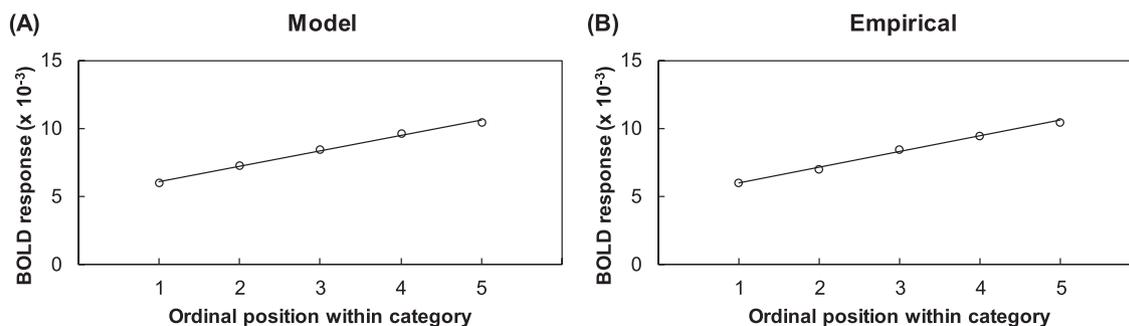
show a linear increase, as empirically observed by [de Zubicaray et al.](#) Note that increasing the number of boosts only once over ordinal positions is not an option for the model of [Oppenheim et al. \(2010\)](#), because it assumes that the RT effect directly reflects the number of boosts.

#### 4.2. Semantic blocking effects

The WEAVER++ model also explains the semantic interference effect in blocked-cyclic naming. In the homogeneous condition, pictures from the same semantic category are named (e.g., fork, glass, spoon, cup, knife), and therefore conceptual bias will delay the selection of the lemmas of pictures later in a cycle, which increases RTs. In the heterogeneous condition, pictures from different semantic categories are named (e.g., fork, swan, axe, bed, mouth), and consequently, conceptual bias will not delay lexical selection for pictures later in a cycle. [Schnur et al. \(2006\)](#) examined blocked-cyclic naming using four cycles, and observed semantic facilitation in the first cycle and semantic interference in cycles two to four, with the interference increasing over these cycles. In experiments assessing the blocking effect for six cycles, [Shao, Roelofs, Martin, and Meyer \(2015\)](#) obtained semantic interference in picture naming regardless of cycle in Experiment 1 (cf. [Belke, 2008; Damian & Als, 2005](#)) and semantic facilitation in the first cycle and semantic interference in later cycles in Experiment 2 (as [Schnur et al.](#) observed). [Fig. 8](#) shows the simulation results together with the real data from this second experiment.

The figure shows that the model captures the semantic interference effect, which increased over cycles. As observed in other studies (e.g., [Hughes & Schnur, 2017](#)), the interference increases between the first and third cycles and levels off in later cycles. However, [Shao et al. \(2015, Experiment 2\)](#) observed semantic facilitation in the first cycle, which is not captured. The model does not explain why semantic facilitation rather than semantic interference may be obtained in the first cycle. It should be noted that the models of [Howard et al. \(2006\)](#) and [Oppenheim et al. \(2010\)](#) also do not explain this.

To account for the semantic facilitation in the first cycle, [Abdel Rahman and Melinger \(2007\)](#), [Belke \(2013\)](#), and [Damian and Als \(2005\)](#), among others, argued that facilitation at the conceptual level outweighs competition at the lexical level in the first cycle, yielding semantic facilitation in the RTs. Based on a meta-analysis of studies in the literature, [Belke \(2017\)](#) argued that the semantic facilitation in the first cycle has a strategic origin, because its presence depended on the design of an experiment. Semantic facilitation was observed in the RTs when the series of homogeneous cycles of different categories were grouped but not when homogeneous and heterogeneous series of cycles alternated. This suggests that with grouping, participants are more likely to strategically exploit the knowledge that all pictures in homogeneous cycles are from the same semantic category, whereby the benefit of this knowledge offsets lexical competition in the first cycle. Still, [Shao et al. \(2015\)](#) used a design with alternating conditions, and obtained semantic interference (Experiment 1) and semantic



**Fig. 7.** BOLD response in left inferior frontal gyrus in the continuous naming paradigm: (A) simulation results and (B) empirical observations by [Canini et al. \(2016\)](#). Linear trend lines are added. BOLD = Blood-oxygen-level dependent.

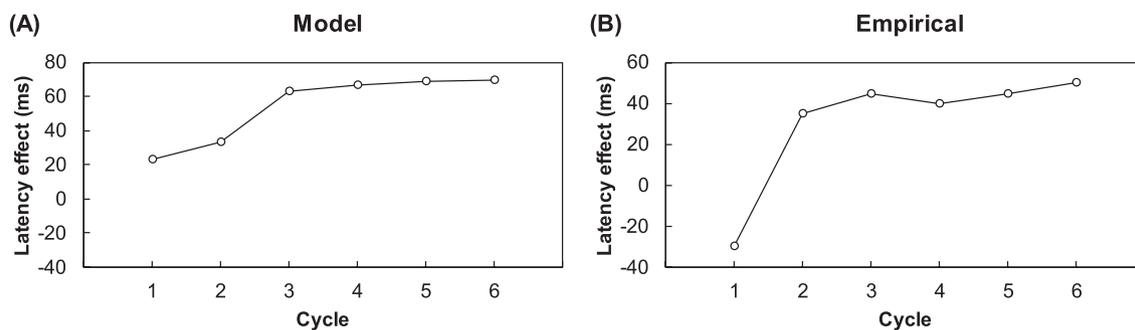


Fig. 8. Behavioral latency results in the blocked-cyclic paradigm: (A) simulation results and (B) empirical observations by Shao et al. (2015, Experiment 2). The latency effect concerns the difference between the homogeneous and the heterogeneous blocks.

facilitation (Experiment 2) in the first cycle. This suggests that grouping of series of homogeneous cycles is not necessary to obtain semantic facilitation. Navarrete et al. (2014) argued that semantic facilitation rather than semantic interference should be regarded as the basic effect not only for the first but also for the later cycles. However, Belke, Shao, and Meyer (2017) provided evidence that the semantic facilitation in the later cycles obtained with the specific experimental design of Navarrete et al. was strategic. To conclude, the available evidence suggests that the semantic facilitation in the first cycle has a strategic origin.

To explain why the semantic interference effect in later cycles is typically not cumulative for healthy speakers (Belke & Stielow, 2013), it may be assumed that the cumulateness is counteracted by a strategic increase of top-down control (cf. Belke, 2008, 2013, 2017). This may be achieved in WEAVER++ by increasing the magnitude of the top-down enhancement (for a given duration), which reduces semantic interference. Perhaps the cumulateness may similarly be counteracted in the model of Oppenheim et al. (2010) by increasing the value of the boost factor.

The WEAVER++ model explains the semantic interference effect in blocked-cyclic naming by assuming a conceptual origin (i.e., conceptual bias) and a lexical locus (i.e., selection by competition). In contrast, Damian and Als (2005) argued that semantic blocking effects are due to either an incremental strengthening of the connections between concepts and lemmas, an increase of resting levels of the activation of lemmas, or a bias at the lemma level. An origin of semantic interference at the lemma level would predict a semantic blocking effect for word naming with a gender-marked determiner, as Damian et al. (2001) observed for Dutch. However, this effect was not replicated by Belke (2013) for German. Also, as we saw, cumulative semantic interference is not obtained for word naming with a gender-marked determiner in German and Italian (Belke, 2013; Navarrete et al., 2010).

Earlier (in Section 4.1.1), I argued that the different direction of the cumulative semantic effect in picture naming (interference) and picture classification (facilitation) occurs because the different pictures within a semantic category map onto different competing responses (i.e., spoon, fork, and cup map onto “spoon”, “fork”, and “cup”) in picture naming (yielding semantic interference) but onto the same response (here, “man-made”) in picture classification (yielding semantic facilitation). This also explains the semantic interference in the word-picture and picture-picture matching tasks used by Schnur and colleagues (Harvey & Schnur, 2016; Wei & Schnur, 2016). On each trial in the word-picture matching experiments of Harvey and Schnur, a written probe word was presented (e.g., cat) followed by four pictures (e.g., dog, bear, sheep, and cat). The participants indicated the matching picture by tapping it on a touch screen monitor (the picture locations were top left, top right, bottom left, and bottom right). In a homogeneous block of trials, the four pictures were always category members and in a heterogeneous block they were not. Half the participants in the experiment of Wei and Schnur performed a word-picture matching task and the other half a picture-picture matching task. On each trial, a probe word or picture (e.g., cat) was presented in the center of a screen

surrounded by four pictures (e.g., honey, yarn, bamboo, and banana). The participants indicated the associated picture (here, cat and yarn are semantically associated) by pressing one of four arrow keys corresponding to the picture location (top, bottom, left, or right from the center). In a homogeneous block, the probes on consecutive trials were category members (e.g., bear, cat, panda, and monkey), and in a heterogeneous block they were not. In these studies, semantic interference was obtained (i.e., longer RTs in the homogeneous than heterogeneous condition) for word-picture and picture-picture matching. In the experiments, the different concepts within a semantic category map onto different competing responses (i.e., different tapping or key press responses). For example, in the experiment of Wei and Schnur, the probe picture of a bear maps onto the manual response for “honey”, cat onto “yarn”, panda onto “bamboo”, and monkey onto “banana”. Thus, according to the WEAVER++ model, semantic interference should be obtained, as empirically observed by Schnur and colleagues.

#### 4.3. Semantic distractor effects

Elsewhere, I showed by computer simulations that the WEAVER++ model accounts for semantic effects in RTs obtained with the picture-word interference paradigm (e.g., Levelt et al., 1999; Piai et al., 2014; Roelofs, 1992, 1997a, 2003, 2004, 2007, 2008a, 2008b). According to the model, the lemma of a semantically related distractor word (e.g., the word *glass* in naming a fork) receives activation from the target picture (via the conceptual links) and is therefore a stronger competitor to the picture name than an unrelated distractor word (e.g., *swan*), which is not activated by the picture. As a consequence, semantic interference is obtained in picture naming. Moreover, in semantically classifying the picture (e.g., say “tableware” to a picture of a fork), semantic facilitation is obtained (e.g., Glaser & Dünghoff, 1984; Roelofs, 2003, 2008b), similar to the cumulative semantic facilitation in picture classification in the continuous paradigm (Belke, 2013). In picture classification, the picture (fork) and distractor word (*glass*) are mapped onto the same lemma response in the semantically related condition (*tableware*). However, in the unrelated condition, picture (fork) and distractor word (*swan*) are mapped onto different lemma responses (*tableware* and *animal*), which compete for selection. As a consequence, responding will be faster in the semantically related than in the unrelated condition, as empirically observed.

The models of Howard et al. (2006) and Oppenheim et al. (2010) do not include assumptions about word recognition, which makes it difficult to apply these models to picture-word interference. Under the simplest assumption, a perceived distractor word activates the corresponding lexical node. In the semantically related condition, this lexical node will also be activated by the picture, whereas this will not happen in the unrelated condition. Thus, in the model of Howard et al., inhibition will be greater for semantically related distractor words than for unrelated ones, presumably yielding semantic interference in picture naming. In the model of Oppenheim et al., lexical nodes do not inhibit each other. However, if lexical selection is by competition (i.e., a

lexical node is selected when its activation exceeds a critical difference relative to the activation of other nodes), then presumably semantic interference will occur in picture naming. Oppenheim et al. argued that the cumulative semantic and semantic blocking effects may be explained without the assumption of competitive selection. Simulations demonstrated that in their model, these effects occur because of competitive learning of the weights of the connections between concepts and lexical items, regardless of whether lexical selection is by competition or not. However, an explanation of the semantic distractor effect in picture naming requires the assumption of selection by competition, unless one assumes that this effect does not arise in lexical selection but elsewhere, like in an articulatory buffer (Finkbeiner & Caramazza, 2006). Earlier (in Section 2.3), we saw that electrophysiological and hemodynamic evidence suggests that the semantic distractor effect arises in lexical selection rather than in an articulatory buffer. To accommodate this evidence, the model of Oppenheim et al. must assume that lexical selection is by competition.

To account for semantic interference across languages in picture naming, the models of Howard et al. (2006) and Oppenheim et al. (2010) have to assume that lexical items of different languages compete for selection. However, this assumption is challenged by the observation that distractor words that are the translation equivalents of the picture name (e.g., the German word *Gabel* in naming of a fork in English) reduce picture naming RT relative to unrelated distractor words. Elsewhere, Roelofs et al. (2016) demonstrated by means of computer simulations that the WEAVER++ model not only accounts for cross-language semantic interference, but also for the facilitation from translation equivalents. For example, in naming a fork in English (say “fork”), the semantically related German distractor word *Löffel* will activate the lemma of its English translation equivalent *spoon*, which competes for selection with the lemma of the English picture name *fork*, whereas the unrelated German distractor word *Ente* activates the lemma of the English word *duck*, which competes less than *spoon*. This yields cross-language semantic interference. When the distractor word is the German translation of the picture name (*Gabel*), the lemma of the English picture name *fork* will be activated but the lemma of *Gabel* will not compete for selection (because it is in the non-target language), yielding facilitation.

Finally, in picture-word interference experiments, the semantic interference in picture naming and the semantic facilitation in picture classification have characteristic time courses. When the SOA is manipulated, semantic interference peaks at short SOAs, whereas semantic facilitation increases with increasing distractor preexposure. Elsewhere (Roelofs, 1992, 2003), it has been demonstrated by means of computer simulations that the WEAVER++ model accounts for the SOA findings. It is unclear whether the model of Howard et al. (2006) can account for these data. It would seem that in this model, semantic interference should increase with increasing distractor word preexposure in picture naming, because presenting the distractor word earlier would give it more time to build up inhibition of the picture name. This would predict an increase of semantic interference with increasing distractor preexposure, whereas a decrease is empirically observed (e.g., Glaser & Dünghoff, 1984). Moreover, in picture classification, the distractor word (*glass*) would inhibit all other words, including the superordinate name (*tableware*) that is now the target. Thus, it is unclear how semantic facilitation may occur in picture classification in the model. It is also uncertain whether the model of Oppenheim et al. (2010) can account for these SOA findings. After conceptual features are activated, the activation of the lexical nodes is updated via a logistic function based on the activation of the conceptual features. Next, the activation of each lexical node is multiplied by a constant boosting factor, until the activation of one of the nodes exceeds threshold and selection occurs. Perhaps the same logistic function may be used for updating the activation of lexical nodes based on the distractor word. However, time does not play any role in the updating function. As a consequence, semantic effects would be independent of distractor preexposure SOA,

unlike what is empirically observed.

Adding a conceptual bias to WEAVER++ simulations of picture-word interference does not harm the model’s ability to simulate semantic distractor effects. Simulations revealed that semantic effects from distractor words occur both with and without conceptual bias. For example, Roelofs (1992) reported simulations of the classic picture-word interference study of Glaser and Dünghoff (1984). Adding conceptual bias to these simulations changed the magnitude of the semantic interference effect in picture naming by only 1 ms. Thus, the model provides a unified account of cumulative semantic, semantic blocking, and semantic distractor effects. The challenge is now for the developers of the models of Howard et al. (2006) and Oppenheim et al. (2010) to demonstrate through computer simulations that their models can account for the picture-word interference effects.

## 5. Summary and conclusions

The aim of this article was to address the challenge posed by Howard et al. (2006) to the developers of WEAVER++ to modify the model such that it also accounts for cumulative semantic effects. To explain these effects, it was assumed that selection of a concept creates a temporary bias towards the concept in the subsequent processing of another concept within the same semantic category or theme. Compared to existing accounts that assume long-lasting learning of conceptual-lexical connection weights (Howard et al., 2006; Oppenheim et al., 2010), a temporary conceptual bias more readily explains a number of empirical findings. These findings include the transfer of semantic interference from listening to picture naming and the absence of cumulative interference with lags consistently larger than eight. In addition, the model explains semantic interference (but not facilitation) in blocked-cyclic naming. To provide a proof of concept of the proposed account, I reported the results of computer simulations using WEAVER++.

The computer simulations demonstrated that the inclusion of conceptual bias in WEAVER++ offers a unified account of the semantic effects. The key assumptions of the unified account are (1) lexical selection by competition, and (2) a conceptual origin and lexical locus of the semantic effects. Behavioral as well as neuroimaging findings were discussed. Simulation revealed that the inclusion of conceptual bias did not hamper the model’s account of semantic distractor effects.

To conclude, the work reported above shows that a unified account of semantic effects in the three paradigms is viable, contrary to pessimistic views of this area (i.e., Dell’Acqua et al., 2007; Finkbeiner & Caramazza, 2006; Van Maanen et al., 2009). Of course, a unified account is also preferable over separate accounts based on Ockham’s principle of parsimony. The challenge is now for the developers of the models of cumulative semantic and semantic blocking effects to demonstrate through computer simulations that they can account for the picture-word interference effects.

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