What can we learn about visual attention to multiple words

from the word-word interference task?

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Abstract

In this work we develop an empirically driven model of visual attention to multiple words using the word-word interference (WWI) task. In this task, two words are simultaneously visually presented, a to-be-ignored distractor word at fixation and a to-be-read-aloud target word above or below the distractor word. Experiment 1 showed that low frequency distractor words interfere more than high frequency distractor words. Experiment 2 showed that distractor frequency (high vs. low) and target frequency (high vs. low) exert additive effects. Experiment 3 showed that the effect of the case status of the target (same vs. AlTeRnAtEd) interacts with the type of distractor (word vs. string of # marks). Experiment 4 showed that targets are responded to faster in the presence of semantically related distractors than in presence of unrelated distractors. Our model of visual attention to multiple words borrows from the dual-route cascaded model of reading two principles governing processing dynamics: cascaded interactive activation and lateral inhibition. At the core of the model are three mechanisms aimed at dealing with the distinctive feature of the WWI task, which is that two words are simultaneously presented. These mechanisms are identification, tokenization, and deactivation.

What can we learn about visual attention to multiple words

from the word-word interference task?

In this paper we develop a cognitive model concerned with the vicissitudes of the target and of the distractor in the word-word interference (hereafter, WWI) task (La Heij, Happel, & Mulder, 1990). In the form of the WWI task with which we will be concerned, participants are first presented with a fixation point (e.g. +) which appears at the center of the display. At its offset, two words are simultaneously presented, a distractor word and a target word. The distractor word always appears at the center of the display, i.e. in the position cued by the fixation point. The target word appears either above (50% of trials) or below the distractor. Thus, the target is defined as a function of the position (either above or below) it occupies with respect to the position of the distractor, which always appears centrally. Participants are instructed to read the target aloud and to ignore the distractor.

In the WWI task, the distractor and the target are defined in terms of the position they occupy, i.e. whether at fixation or above/below fixation. Thus, the WWI offers the opportunity to devise a mechanism for binding the lexical/semantic representations of the stimuli with the corresponding visual, pre-categorical features, i.e. to explain how a link between the identity of the items and the positions those items occupies is constructed.

In Experiment 1 of La Heij et al. (1990), the distractors could be: semantically related to the target or unrelated; a member of the response set (i.e the distractor is a possible target) or not (i.e. the distractor is never presented as a target); or irrelevant (i.e. the distractor is selected form a semantic category none of the stimuli of the previous conditions were selected from). Analyses showed that neither of these two manipulated variables exerted a significant influence on the time to read the target aloud, a result that led to the widespread belief that when two words are simultaneously presented and only the word away from the fixation position has to be read aloud, the distractor word (presented at fixation) has no influence on the processing of the target word. La Heij et al. (1990) also included a control condition in which the fixated distractor was composed of a row of five Xs. Interestingly, reaction times (RTs) in the control condition (541 ms) were significantly faster than RTs in the word-distractor conditions (580 ms – averaged across the five conditions). This latter result does suggest that the distractor words did affect target processing, at least in comparison with a non-linguistic distractor condition. Thus, it might be possible that whereas the semantic category of the distractor does not influence target processing (Experiment 4 will put this hypothesis to the test), other non-semantic properties – such as written frequency – of the distractor do. So in our first experiment we manipulated the frequency (High vs. Low) of the distractor words in a WWI task.

Experiment 1

Method

Participants. Thirty-one students of the Università degli Studi di Padova participated in the study as volunteers. They all had normal or corrected-to-normal vision and all were native speakers of Italian.

Design. A within-subject design was employed with Distractor Frequency (high vs. low written frequency) as a factor.

Materials. One hundred and thirty-eight words were selected from the COLFIS database (Laudanna, Thornton, Brown, Burani, Marconi, 1995). Ninety-two words served as distractor words: half of them were of high-frequency (mean: 406; range: 212-808) and half were of low-frequency (mean: 0.7; range: 0.3-1.3). High- and low-frequency words were balanced in terms of number of letters (6.6 vs. 6.6, $t < 1$), number of syllables (2.7 vs. 2.7, $t < 1$) and orthographic neighborhood size (4.0 vs. 3.8, $t < 1$). Forty-six words were used as target words (mean frequency: 33.3; range: 16-85). Each target word was presented twice, once with a low-frequency distractor and once with a high-frequency distractor. Targets were paired with distractors of the same letter length, and phonological overlap between targets and distractors was avoided. All words were shown in Courier New font, lowercase, bold, 18-point size, and printed in black on a white background.

Apparatus. The experiment took place in a sound-attenuated and dimly lit room. The stimuli were displayed on a 17” cathode-ray tube monitor controlled by a 686 IBM-clone and E-prime software. The onset of vocal responses was detected using a high-impedance microphone to which a voice-key was connected.

Procedure. Participants were tested individually. They were instructed to read the target aloud as quickly and accurately as possible disregarding the distractor. On each trial, a fixation point (+) appeared in the center of the screen and between two bars (the distractor always fitted within the position of the two bars; see La Heij et al., 1990) and was presented for 500ms. Following the fixation offset, a blank screen was displayed for 100ms, followed by the simultaneous presentation of the two stimuli , which remained visible until a vocal response was detected or 3s elapsed. The ITI was fixed at 1000 ms. The distractor word was always presented in the center of the screen, i.e. in the place of the fixation point. The target word could randomly appear either above or below the distractor. At a viewing distance of 60cm, the distance between the nearest contours of the words was 0.26 degree of visual angle, and the length of the words ranged from 0.80 to 1.86 degree of visual angle. Target/distractor pairs were presented in a different random order for each participant. The experimenter scored each response as correct or incorrect on a sheet. The experimental session was preceded by a practice session of 11 trials.

Results

Naming errors and apparatus failures (5%) were removed prior to analysis. Correct RTs were submitted to Van Selst and Joulicœur’s (1994) recursive outlier removal procedure, resulting in the elimination of 0.8% trials. Distractor Frequency was treated as a within-subject factor in both the by participants (F1) and the by items (F2) ANOVAs.

RTs. Reading aloud latencies were significantly faster when target words were presented with high frequency distractor words (643 ms) than when they were presented with low frequency distractor words (672 ms), F1(1, 30) = 7.7, MSE = 161, p < .01, F2(1, 45) = 5.2, MSE = 367, p < .05.

Accuracy. Subjects made fewer errors with high frequency words (1.3%) than with low frequency words (2.2%), a difference that just missed significance in the by-subject analyses, F1(1, 30) = 4.1, MSE = 001, p = .05, but was not significant in the by-items analyses, F2(1, 45) = 3.1, MSE = .001, p = .084.

Discussion

The result is clear cut: the frequency of the distractor word does affect the time to read the target word in a WWI task, with high frequency distractors interfering less than low frequency distractors. Although the direction of this effect is counter-intuitive, unrelated low frequency distractors have been proved to interfere more than unrelated high frequency distractors in other paradigms, as the color naming of colored printed words (Monsell, Taylor, & Murphy, 2001) and the picture-word interference task (Miozzo & Caramazza, 2003). Now that we have established that responding in the WWI task is sensitive to manipulations of the distractor stimuli, we are faced with the task of providing an explanation of the results found. That is, why is it that high frequency distractors interfere less than low frequency distractor? To answer to this question, we need a model of how people perform the WWI task. The following sections are devoted to attempting to develop such a model.

The model

An a priori issue: Two words at the same time.

In developing a model of how people perform the WWI task we are faced with a problem which is well captured in the following passage of Allport (1977): “The model [i.e. Morton’s *logogen model* (Morton, 1969)] lacks a specific mechanism for relating particular logogen outputs to the particular stimuli that evoked them. In particular where more than one word, or nameable item, is presented at the same time, a mechanism is clearly required to integrate appropriately the nominal identities of the items – their logogen output – with their other physical attributes – location, color, size, etc.” (p. 525). Again, a few lines later: “Given a specialized linguistic mechanism concerned uniquely with the lexical identity of word stimuli regardless of their ‘precategorical’ stimulus attributes, that is, a logogen system, performance and phenomenology alike call for the integration of information from both the logogen system and the mechanisms responsible for the analysis of visual form and location” (pg. 525). Allport here is calling for a system where a word’s perceptual features and its identity are bound together to form an episode. In the WWI procedure, the distractor is defined in terms of the position it occupies i.e. it is at fixation, whereas the target is not at fixation. So whatever model is developed, it has to explain how a link between the identity of an item and the position that item occupies is constructed, so that the appropriate decision with respect to what to read aloud and what to ignore can be taken – that is, a solution to the well-known "binding problem" is required.

This general issue of binding stimulus position to stimulus identity can be dealt with by considering the underlying process as composed of two logically separable, although interdependent, processing stages. First, the system needs to provide a precategorical, purely visual, episodic representation of each stimulus; i.e., a representation to which the position of the stimulus is bound. A model devoted to the processing of multi-object scenes the outputs of which are visual representations of objects bound to their positions, the Multiple Slots Multiple Spotlights model ($(MS)^2$), has recently been proposed (Hayworth, 2009; Hayworth, Lescroart, & Biederman, 2011) and will be briefly described in the following section.

This temporary episodic visual representation of a stimulus needs to be linked to the permanent representation of that stimulus in lexical/semantic memory. In other words, the stimulus needs to be identified and once it has the system can operate on it – for example, when the task is the WWI task, the system can at that point decide to read the stimulus aloud (if it is not at fixation), or to ignore it (if it is at fixation).

The Multiple Slots Multiple Spotlights model and the concept of a proto-word

Upon the presentation of a two-object display, the $(MS)^2$ model (see Hayworth (2009) and Hayworth et al. (2011) for a detailed discussion of the model) posits that the visual system segregates the background from the features of the objects, dynamically binds the features belonging to each object, and then allots each object's bundled features to separate 'slots', each composed of a distinct set of units (neurons). The units in each slot encode the features of only one object in the scene and do so in a way that is independent of the absolute or relative position of the object. In this sense, the slots can be seen as *object files* (Kahneman, Treisman, & Gibbs, 1992): temporary structures in which information accrues over time. If, for example, the object changes, the object file is updated, thus creating a perceptually continuous entity.

Information regarding the position of each object is explicitly associated with each object file, or slot. Crucially, the population of units representing the position linked to the object assigned to a given slot constitute a distinct set of units from the population of units devoted to the representation of the features in that slot. In other words, position and content are representationally separated but bound. Units representing the object's position can be then thought of as pointers linking the corresponding object file to the object position.

When the system is presented with the two words of a WWI task, the $(MS)^2$ model hypothesizes that the features of each word are segregated from the background, dynamically bound together, and loaded in two distinct slots, one representing the stimulus presented at fixation (the distractor) and one representing the stimulus not presented at fixation (the target). The relative position information 'fixation' and 'not at fixation' are represented separately and bound to the corresponding slot. In this way, the total display is provided with a syntactic structure that allows the type of symbolic manipulation required to account for the performance in the WWI.

Early in processing, the contents loaded in the slots - the object files corresponding to the words - consist of visual, pre-categorical codes corresponding to the two words presented: at this stage; the words have not yet been identified as words, but instead are organized bundles of the visual features of the word, or *proto-words*. To account for the performance in the WWI task, we now need a theory of how those proto-words activate the content stored in lexical/semantic memory, that is, a theory of how orthographic, phonological, and semantic information is retrieved from memory and assigned to the visual code generated so far. Such a theory will be developed in the next sections.

Types and Tokens

The distinction between types and tokens recurs many times in the psychological literature (e.g. Jackendoff, 1983; Chun, 1997; Bowman & Wyble, 2007; Kanwisher, 1987, 1991). A *type* includes all the known properties of an item (including, e.g., its orthographic and phonological representations, its semantics, the phonemes it comprises) that are stored in lexical/semantic memory. Thus, activating the type of a word constitutes activating its orthographic representation, its semantic representation, its phonological representation, and its phonemes. A *token* instead is a particular exemplar of a given type encountered in a given occasion; that is, it is an episodic, instance-specific representation.

The representation of a linkage between a proto-word and a type is a token, which acts as a pointer to the type associated with this proto-word. Thus, the type can be re-activated, or regenerated when required. Once a token is added to an object-file, that object-file includes all of the information necessary to perform the WWI task: the visual code of the stimulus, the position of the stimulus, the identity of the stimulus and the orthographic, semantic, phonological and phonemic representations of the stimulus.

The dual route cascaded (DRC) model of reading: a theory of type activation

In Experiment 1 we manipulated the frequency of the distractors and found that low frequency distractors interfere with reading aloud of targets more than high frequency distractors do. The frequency with which words occur in a language is information stored in the lexical system (Morton, 1969), i.e. stored in long term memory. Thus, to account for the results of experiment 1 – and, more generally, for the performance in the WWI task – we need a theory of how lexical information is accessed, that is, in our terms, of how types are activated. Here, we will use as a reference framework the DRC model (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) of visual word recognition and reading aloud, and, particularly, the lexical reading route of that model.

The DRC model's lexical route consists of two interconnected lexicons. Letter units, which are activated upon stimulus presentation, activate words in an orthographic lexicon. Activation in the orthographic lexicon activates in cascaded fashion letter units via feedback connections and units in a phonological lexicon via feedforward connections. Activation from the phonological lexicon feeds forward to a phoneme system and backwards to the orthographic lexicon.

When entry A and entry B are both active in one of the DRC lexicons, resolution is achieved by one of these entries driving the other entry's activation down to zero, via lateral inhibition. In the DRC model, lexical inhibition (both within the orthographic and the phonological lexicon) is homogeneous i.e. each unit inhibits any other unit in the lexicon to the same degree, regardless of its identity.

Activation in orthographic and phonological units that represent high frequency words grows faster than activation in orthographic and phonological units that represent low frequency words.

The reading-aloud response is produced when the activation in the phoneme units reaches a pre-established threshold. The time needed to reach this threshold constitutes the model's reaction time.

Letter sets

We hypothesize that the appearance of a row of letter-like stimuli – a proto-word – causes the construction of a set of letter-detectors for analyzing that row. If two rows appear, as in the WWI paradigm, two sets of letter units are constructed. These are constructed and operate in parallel and are functionally independent. We will test this proposal in Experiment 3.

One might argue that as two letter sets are constructed, then also two lexicons are constructed. Reduplication of the entire network has been for example implemented in some versions of the TRACE model (McClelland & Elman, 1986; see also McClelland, 1986) to allow processing of more than one word at a time. This is not a solution we can adopt since it predicts that lexical processing of the distractor and lexical processing of the target are independent, and we know, from Experiment 1, that the distractor does exert lexical effects on target processing.

Assumptions concerning visual attention

Attention is rapidly and transitorily deployed in response to any visual stimulation. This attentional resource is nonspecific and it amplifies all input. In the absence of a spatial cue, attention is spread around fixation and amplifies both the distractor and the target. However, visual processing efficiency decreases as distance from fixation – that is from the fovea – increases, which means that in the WWI paradigm distractors are processed more efficiently than targets, at least early on in processing.

Type activation, identification, tokenization, and deactivation

The presentation of a word or nonword causes the construction of a dedicated letter-detector set whose letter units send activation forward to the orthographic lexicon. Activation then cascades forward to the following levels and back to the letter level currently feeding the lexicon, in an interactive-activation fashion.

Activation in the units accrues over time. We hypothesize that there exists an *identification threshold* in the orthographic lexicon. Word identification corresponds to activation in one of the orthographic units having reached the identification threshold.

A further assumption we make is that upon the presentation of a stimulus under optimal viewing conditions, processing up to the point of identification is ballistic - that is, it cannot be interrupted before that point.

The first consequence of identification is that the identified word is tokenized - that is, a token is created. In our view, tokenization must follow identification, i.e., a non-identified unit cannot be tokenized - otherwise any activated lexical unit can potentially be tokenized, and this has unwanted consequences. For example, suppose the input word has an orthographic neighbor and that this neighbor is activated upon the presentation of that target word for reading. If tokenization occurs as soon as something gets active in the lexicon, then both the word and its neighbor would be tokenized, i.e. an episodic trace of a stimulus that *had not been presented* (the neighbor) would been made available to the system. That would be a perceptual hallucination. But if we do introduce an identification threshold, then only the unit that has reached an *interesting* level of activation is tokenized.

A token is a temporary link between the orthographic-lexicon representation that has reached the threshold for identification and the object-file currently feeding the system. Tokenizing a word does not mean copying the type into the object file; it means setting a pointer from the object file to the type activated. A token is thus bound to both the type and the object file (Treccani, Cubelli, Sellaro, Umiltà, & Della Sala, 2012). We propose that the token is created in working memory and consist of a self-sustained unit. By means of a token, information regarding both the type and the visual features of the stimulus – e.g. its relative position – can be accessed. That is, once a token has been formed, the system knows whether a given stimulus is presented at fixation or not, and thus it knows whether a given stimulus is the distractor or the target.

If the activation is not coming from the target – that is, is being generated by the distractor - , then identification has a second consequence: *deactivation*. If the orthographic lexical entry identified is that of the target, the system will continue to support processing until reading aloud occurs. However, if a tokenized orthographic lexical entry is classified as the lexical entry of the distractor, the system suspends input to that that orthographic lexical unit by blocking the output from the letter detector set (remember here that each of the stimuli has a dedicated letter detector set, so that operating on one of these does not affect processing within the other one). The idea here is that once this feeding is suspended, lexical and semantic activation is not supported anymore. When not supported, activation in the lexical and semantic units decays back to the resting level. That is, lexical and semantic units are deactivated.

Note that suspending the feeding of activation from the letters to the orthographic representation does not, in itself, result in the deactivation of that orthographic representation: after suspension – and in the absence of any other mechanism – the orthographic representation maintains its level of activation. This state of affairs has an unfortunate theoretical consequence, namely that, if the orthographic representation of the distractor maintains its level of activation even after input to it ceases, that unit continues to send activation to the connected phonological unit, which – in turn – continues to send activation to the units representing the phonemes it comprises, and this goes on until reading aloud occurs. But what will be produced here is not the target, but the distractor.

Therefore, there needs to be a mechanism that – working conjointly with the suspension of letter-to-orthography activation – brings the activation of the distractor's orthographic lexical entry back to its original resting level. This mechanism in the DRC model that allows this is 'intrinsic decay'. Intrinsic decay is a parameter associated with each unit in the model. What this parameter does is to subtract a proportion of activation from any unit in each processing cycle, thus reducing the computed activation of that unit.

Thus, if a tokenized lexical entry is classified as the lexical entry of the distractor, the system suspends the feeding of the corresponding orthographic unit by blocking the output from the letter detector set. This orthographic representation then starts to decay, and it decays down to its resting level. Note that before the activation of the distractor's orthographic representation has declined to zero, this orthographic unit will continue to feed the connected phonological and semantic units. However, the input of the orthographic representation to these higher levels will decrease over time. Once the input from the orthographic unit gets weaker than the decay parameters associated with the semantic and phonological units, the activations of the distractor's semantic and phonological units will start to go down, eventually reaching their original resting levels. Deactivation, therefore, *propagates*.

Why is there a distractor frequency effect?

Given the assumptions concerning visual attention (see above), which imply that visual/attentional distractor processing is – early on in processing – more efficient than target processing because the distractor is at fixation, it follows that the distractor will contact the orthographic lexicon earlier than will the target.

As previously mentioned, representations in the lexicons inhibit each other through homogeneous lateral inhibition. The first orthographic lexical unit in which activation will begin to rise is that of the distractor: as the activation in this unit rises, the unit sends inhibition to all the remaining units in the orthographic lexicon, thus preventing their activation. That is, while the distractor representation is being processed, no other representations – among which is the target's representation - can be concurrently active. This constitutes a functional bottleneck for target processing.

Processing of the distractor's lexical representations continues until identification occurs. As soon as the distractor's orthographic representation reaches the identification threshold and a token is created, the activation of that representation begins to decay because input to it ceases. Decay continues down to the resting level. As the activation in the distractor's lexical units declines, the inhibition that these units sends to any other units in the lexicon weakens. When this lateral inhibition becomes weak enough, the activation of the target's lexical units can start to rise and will continue to rise until the reading-aloud response is made.

The distractor frequency effect receives, within this framework, the following explanation. The activation in an orthographic lexical unit representing a high frequency distractor will rise more quickly than the activation in an orthographic lexical unit representing a low frequency distractor. As a consequence, high frequency distractors will be identified earlier than low frequency distractors. Since high frequency distractors are identified earlier than low frequency distractors, activation will begin to decay sooner for the former stimuli than for the latter stimuli. Thus, activation of the target's representations starts to rise earlier when the target is presented with a high frequency distractor word than when the target is presented with a low frequency distractor word.

A prediction from the model

Distractor frequency affects the time required for the orthographic lexical representation of the distractor to reach the identification threshold, with high frequency distractors reaching this threshold earlier than low frequency distractors. The identification threshold, however, is set to the same value irrespective of the stimulus frequency. So the time required for the distractor's lexical unit to be fully deactivated (i.e. to return to the resting level) once decay has begun will not be affected by the frequency of the distractor. In other words, the slope of the deactivation is unaffected by frequency. Thus, although low frequency distractors delay the start of the target activation more than high frequency distractors do, high and low frequency distractors affect the rising of the activation – the slope – of the target in the same way.

Hence our model predicts that the effect of any variable affecting the rate at which activation of the target's orthographic lexical entry rises will not be influenced by the frequency of the distractor. According to the model, a variable that affects the rate at which lexical activation rises is word frequency. Therefore the model predicts that the size of the target frequency effect will be independent of distractor frequency (i.e. target frequency and distractor frequency will have additive effects). We tested this prediction.

Experiment 2

Method

Participants. Forty students of the Università degli Studi di Padova participated in the study as volunteers. They all had normal or corrected-to-normal vision and all were native speakers of Italian.

Design. A 2x2 factorial design with Distractor Frequency (high vs. low frequency) and Target Frequency (high vs. low frequency) as within-subject factors was used.

Materials. The ninety-two words used as distractors in Experiment 1 were also used as distractors in this experiment. Ninety-two new words were selected from the Colfis database (Laudanna et al., 1995) and used as target stimuli: 42 were high-frequency words (mean: 310; range: 119-740) and 42 were low-frequency words (mean: 1.9; range: 0.3-5.9). High- and low-frequency targets were balanced in terms of number of letters (6.9 vs 6.9, $t < 1$), number of syllables (2.9 vs 2.89, $t < 1$) and orthographic neighborhood size (2.8 vs. 2.6, $t < 1$). Each target was presented twice, once with a low-frequency distractor, once with a high-frequency distractor. In each target-distractor pair, words were of the same letter length. In each pair, phonological overlap between target and distractor was avoided.

Apparatus. See Experiment 1.

Procedure. The procedure was the same as that of Experiment 1, except that the position of target words was controlled and counterbalanced across participants. Two lists were constructed: in the first list, half of the targets in each condition was presented above the distractor and the other half below; in the second list, the pairing between targets and positions was reversed. The presentation of the two lists was counterbalanced across participants.

Results

Naming errors and apparatus failures (3.2%) were removed prior to analysis. Correct RTs were submitted to Van Selst and Jolicœur (1994) recursive outlier removal procedure, resulting in the elimination of 0.9% trials. Distractor Frequency (high vs. low frequency) and Target Frequency (high vs. low frequency) were both treated as within-subject factors in the by participants ANOVA (F1), whereas in the items ANOVA (F2) Target Frequency was treated as a between-subjects factor and Distractor Frequency as a within-subject factor.

Mean correct RTs and error rates are reported in Table 1.

INSERT TABLE 1 ABOUT HERE

RTs.. The analysis revealed a significant main effect of Target Frequency, F1(1, 39) = 39.3, MSE = 15721, p< .001, F2(1, 90) = 10.7, MSE = 18560, p < .005, and a significant main effect of Distractor Frequency F1(1, 39) = 10.7, MSE = 4410, p < .005, F2(1, 90) = 11.8, MSE = 5262, p < 005. Crucially, the interaction between the two factors was not significant, Fs <1.

Accuracy. There were no significant effects in the analysis of errors, Fs < 1.

Discussion

Low frequency distractors interfered with target reading more than high frequency distractor, thus replicating the result of Experiment 1. In addition, high frequency targets were read faster than low frequency targets. Critically, distractor frequency and target frequency exerted additive effect on RTs. This latter result is congruent with the prediction of the model, which posits that distractor frequency affects the moment in time in which the lexical representations of the target start to be activated, but not the rate at which their activations rise, which is however a function of the target frequency, with activation of high frequency targets rising more quickly than the activation of low frequency targets.

Dedicated letter detector sets: prediction and evidence

We have previously proposed that the appearance of a row of letter-like stimuli – a proto-word – causes the construction of a set of letter-detectors for analyzing that row. Also, if two rows of letter-like stimuli appear simultaneously, as in the WWI task, then two sets of letter units are constructed in parallel (i.e. concurrently). These two letter sets are – by hypothesis – functionally independent: processing within one set of letter units does not affect processing within the other set, and processing in the two sets unfolds in parallel. However, both sets feed into a single common orthographic lexicon.

Whereas processing within the letter sets unfold in parallel, processing of the two stimuli within the lexical system does not unfold in parallel. As argued above, the activation of the type corresponding to the distractor and the activation of the type corresponding to the target constitute two distinct operations: while the system is activating the lexical representations of the distractor, the activation of the lexical representations of the target is blocked via lateral inhibition, and so has to wait until after identification of the distractor has occurred and decay is triggered. Activation of the lexical representations of the distractor thus bottlenecks activation of the lexical representations of the target. It is important to note that, although during the bottleneck the lexical representations of the target cannot be activated, processing within the letter set devoted to the target can go on, since this letter set works independently from distractor processing. This state of affairs leads to the prediction that the effects of a variable affecting target-letter processing should be absorbed (at least partially) into the bottleneck when the target is accompanied by a distractor word, but not when it is presented without a distractor word, since in this latter case there would not be any bottleneck.

Suppose we concurrently manipulate two variables. One variable is whether the target is presented with an unrelated distractor word or with a nonorthographic control stimulus (e.g. a string of # marks, which we assume would not be treated as a proto-word). Since the control stimulus will not activate any lexical representations and thus will not induce any bottleneck, the prediction with respect to the effect of this manipulation is that target naming should be slower in the distractor word condition with respect to the control, nonorthographic stimulus condition. The second variable is whether the target is presented degraded or clear, for example either printed in alternated case (eLEpHanT) or printed in same case (ELEPHANT). With respect to this latter manipulation, it is known that same case stimuli are read faster than alternated case stimuli (e.g., Mayall, Humphreys, & Olson, 1997; Besner & McCann, 1987). We will assume that this case alternation affect arises within the letter-detector level. Here the model put forward so far makes an interesting prediction with respect to the interaction of these two variables. This model predicts that the case alternation effect will be smaller when the target is accompanied by a distractor word than when the target is accompanied with a nonorthographic stimulus.

The reason is the following. When the distractor stimulus is not a proto-word, it does not cause the construction of a letter detector set, and so the system engages immediately with the processing of the target. As a result, in this condition the case alternation effect will be fully present. However, when the distractor is a word, the system has to process the distractor up to its identification, and this takes time. During this time, the processing of the target's letters continues. As a result, the benefit derived from the letters being all printed in the same case will be reduced or eliminated, i.e. the case alternation effect will be smaller or absent.

This latter prediction is tested in the experiment reported below.

Experiment 3

Method

Participants. Thirty-two students of the Università degli Studi di Padova participated in the study as volunteers. They all had normal or corrected-to-normal vision and all were native speakers of Italian.

Design. A 2x2 factorial design with Target Case (same case vs. AlTeRnAtEd case) and Distractor Type (word vs. string of # marks) as within-subject factors was used.

Materials. Fifty-two target words and 26 distractor words were selected from the COLFIS database (Laudanna et al., 1995). Each target word was presented in each of the four conditions, i.e. in same and alternated case and paired with either a string of # marks or a word. In each target-distractor pair, the target was of the same length (i.e. number of characters/# marks) of the distractor. In each pair, phonological overlap between target and distractor was avoided.

Apparatus. See Experiment 1.

Procedure. See Experiment 2.

Results

Naming errors and apparatus failures (6.9%) were removed prior to analysis. Correct RTs were submitted to Van Selst and Jolicœur's (1994) recursive outlier removal procedure, resulting in the elimination of 0.9% trials. Target Case (same case vs. AlTeRnAtEd case) and Distractor Type (word vs. string of string of # marks) were both treated as within-subject factors in both by participants (F1) and by items (F2) ANOVAs.

Mean correct RTs and error rates are reported in Table 2.

INSERT TABLE 2ABOUT HERE

RTs. The analysis revealed a main effect of Target Case, $F1(1, 31) = 66.4$, $MSE = 1052$, $p < .001$, $F2(1, 50) = 54.7$, $MSE = 1113$, $p < .001$, a main effect of Distractor Type, $F1(1, 31) = 53.9$, $MSE = 1259$, $p < .001$, $F2(1, 50) = 122.9$, $MSE = 450$, $p < 001$. It is important to note that the interaction between Target Case and Distractor Type was significant, $F1(1, 31) = 4.6$, $MSE = 529$, $p < .05$, $F2(1, 50) = 4.2$, $MSE = 450$, $p < .05$. The Target Case effect was smaller in presence of a word as distractor than in presence of a string of # marks as distractor. Pairwise comparisons revealed that the Target Case effect was significant in both Distractor Type conditions ($t1(31) = 7.2$, $p < .001$, $t2(206) = 5.2$, $p < .001$, and $t1(31) = 6.7$, $p < .001$, $t2(206) = 4.1$, $p < .001$, for word and string of # marks respectively).

Accuracy. There were no significant effects in the analysis of errors, $Fs < 1$.

Discussion

Word distractors interfere with target reading aloud more than nonorthographic distractors. Same case targets are read aloud faster than alternated case targets. Crucially, the two variables interact: the effect of the target case status is significantly larger when the target is accompanied with a nonorthographic distractor than when the target is accompanied with a word distractor. This latter result is what is predicted by the model, which posits that despite target lexical processing being put into suspension by the lexical processing of the word distractor, target letter processing can continue, since target letters and distractor letters are processed within two independent sets of letter detectors.

Target – Distractor semantic relatedness

In the picture-word interference task, a picture is presented along with a superimposed distractor word. Participants are instructed to name the picture and to ignore the distractor word. A semantically related word interferes with picture naming more than an unrelated word: this is the semantic interference effect (La Heij, 1988). Within the Weaver++ model of word production (c.f., Levelt, Roelofs, and Meyer, 1999; Roelofs, 2003), semantic interference is ascribed to the stage of lexical (lemma) selection and arises because, when the word distractor is semantically related to the target picture, the target contributes to the activation of the distractor's lemma through spreading of activation in the semantic system ('reverse priming', Neumann, 1986), which has the consequence of making the distractor a stronger competitor for selection.

The picture-word interference task bears an obvious analogy with the WWI task, in that in both tasks the target is accompanied with a distractor that needs to be rejected, and in both tasks a phonological code needs to be activated. There is however an important difference between picture naming and word reading aloud (e.g., Glaser and Glaser, 1989; Warren and Morton, 1982), namely, the ease with which phonological representations are activated (La Heij et al, 1990). In picture naming, phonology is accessed by means of activation of semantic representations, which is followed by the selection of a lemma, which in turn is followed by the activation of a phonological representation (Levelt et al., 1999). In contrast, when a word is read aloud, its phonological representation is activated directly from the orthographic representation, with little intervention of the co-activated semantic representations (e.g., Mulatti, Lotto, Peressotti, & Job, 2010). For example, McCauley, Parmelee, Sperber, and Carr (1980) noted "the first stage [of picture naming], in which contact is made with semantic memory, seems to be automatic, but the second stage appears to require an investment of attention to consult the internal lexicon for a name. This stands in marked contrast to evidence that when stimuli are words, their stored phonetic codes […] can be activated automatically" (pg. 40). La Heij et al. (1990) suggested that given this difference between picture naming and word reading (namely, whether or not semantic representations must be involved to accomplish the task), "if the distractor […] semantic relatedness […] interfere[s] in the process of picture-name retrieval, the prediction can be derived that these effects will diminish or even disappear when instead of a picture-naming task, a word-reading task is used" (pg. 118). Thus, according to La Heij et al., if there is a semantic relatedness effect at all in the WWI paradigm, this effect will be small (and it will be an interference effect). There is however a third option which they did not mention, which is the possibility that the semantic relatedness effect in the WWI paradigm will be a facilitation, i.e. that targets will be read aloud faster when paired with semantically-related distractor words than when paired with unrelated distractor words.

To pursue our theoretical discussion further, we need at this point to offer a slightly more detailed conception of the nature of the semantic system – to consider just what the units in that system represent. Two possibilities have been considered in the previous literature. One is that each semantic unit stands for a whole concept ("compositional semantics'); on this view, semantic-relatedness effects arise because there are excitatory links between units representing semantically-related concepts. The other possibility is that each semantic unit stands for a semantic feature ("decompositional semantics"); on this view, semantic relatedness effects arise because two semantically-related concepts have many semantic features in common.

These are different views, but they have an important feature in common: that both are inconsistent with the idea that there are lateral inhibitory links between the units in the semantic system. On the first view, these links are not inhibitory but facilitatory (c.f., Schmidt, Cheesman, & Besner, 2013), with the strength of the facilitatory link between two units being proportional to the semantic similarity of the two concepts represented by those units. On the second view, since a semantic representation consists of the simultaneous activation of many semantic feature units, one would not want mutual inhibition to occur between semantic units. So the semantic system is different from all of the other components of our model: in all of these other components, all the units within a level laterally inhibit each other, but that mustn't be so for the units in the semantic system.

To put this another way: if a letter string activates its orthographic neighbors in the orthographic lexicon (and it is clear that this does happen: for review, see Perea and Rosa, 2000), we need a mechanism to suppress this neighbor activation, because we only want one unit active in the orthographic lexicon; and this is also true for the letter level, the phonological lexicon level, and the phoneme level. So lateral inhibition is needed at all four levels. But it is not needed at the semantic level – indeed, that level would not function appropriately if such lateral inhibition were present there.

Now, suppose in the WWI paradigm we manipulated whether target and distractor were semantically related or not. What effect of semantic relatedness would we predict? As argued earlier, target processing must wait until the activations of distractor-related orthographic and phonological units have been sufficiently weakened by deactivation and its propagation. There are thus two possible scenarios, which hold whichever of the two views about the nature of semantic units is adopted.

In the first scenario, by the time the target processing begins, deactivation and its propagation had already brought the activation of the semantic representations to zero; here, target processing will be unaffected by the semantics of the distractor.

In the second scenario, at the moment at which target activation begins deactivation and its propagation have weakened the distractor's representations but these target representations have not yet completely decayed. So at that moment, if target and distractor are semantically related, the semantic representation of the target will still be partly activated . If the semantic system plays no effective role in reading aloud, then this activation of the semantics of the target will have no effect i.e. there will be no effect of target-distractor semantic relatedness effect seen in the WWI paradigm. But if the semantic system contributes to reading aloud at all, what we will see is semantic facilitation in the WWI paradigm. Hence our Experiment 4 investigated whether there is such an effect.

The effect of semantic relatedness in the WWI task has previously been investigated by La Heij et al. (1990), who reported that in their Experiment 1, there was no effect of distractor-target semantic relatedness on RTs. From this the authors concluded that target-word reading in WWI tasks is immune from effects due to semantic properties of the distractor word. With respect to our model, this null effect is congruent with the proposal that – by the time target processing starts – deactivation and its propagation have zeroed the activation of the distractor's semantic representation.

However, there is a methodological issue with the experiment of La Heij et al. (1990) that might potentially be responsible for the null effect of semantic relatedness they obtained. There were 288 trials in their experiment, but they used only 6 targets. So each subject read aloud each target 48 times. This massive repetition of the targets within the experiment might well have hidden any effect of semantic relatedness, especially if this effect is small.

We wished to discover whether, when repetition effects are minimal, an effect of semantic relatedness might emerge, and if this did happen whether this effect would be a facilitation or an interference. To reduce the impact of target repetition, in the experiment reported below the target was presented to each subject twice only, once with a semantically related distractor and once with an unrelated distractor.

Experiment 4

Method

Participants. Thirty-two students of the Università degli Studi di Padova participated in the study as volunteers. They all had normal or corrected-to-normal vision and all were native speakers of Italian.

Design. A within-subject design was employed with Semantic Relatedness (distractor semantically related vs. unrelated) as factor.

Materials. One hundred and fifty words were selected from the COLFIS database (Laudanna et al., 1995). Fifty words served as targets and one hundred words were used as distractors. Half of the distractors were semantically related to the target words (mean frequency: 9.2; range: 0.31 - 49) and half were semantically unrelated to the target words (mean frequency: 9; range: 0.3 – 32.5). These two groups of distractor words were balanced in terms of number of letters (6.9 vs 7.2, $t < 1$), number of syllables (2.97 vs 2.97, $t < 1$) and orthographic neighborhood size (3.05 vs. 3.03, $t < 1$). Each target was presented twice, one with a semantically related distractor, once with an unrelated distractor. The mean frequency of target words was 9.3 (range: 0.31-58). Phonological overlap between the name of the target and the phonology of the distractor was avoided.

Apparatus. See Experiment 1.

Procedure. See Experiment 2.

Results

Naming errors and apparatus failures (8.4%) were removed prior to analysis. Correct RTs were submitted to Van Selst and Jolicœur's (1994) recursive outlier removal procedure, resulting in the elimination of 0.6% trials. The factor Semantic Relatedness (distractor semantically related vs. unrelated) was treated as a within-subject factor in both the by subject (F1) and the by items (F2) analyses. Mean correct RTs and error rates are reported in Table 3.

INSERT TABLE 3 ABOUT HERE

RTs. The 29 ms facilitation due to semantic relatedness was significant, F1(1, 31) = 6.25, p < .05, F2(1, 49) = 4.24, p < .05.

Accuracy. Subjects made fewer errors with semantically related distractors (0.4%) than with unrelated distractors (0.5%), a difference that was however not significant, Fs < 1.

Discussion

When the target stimuli in a WWI task are repeated only twice within the experiment, semantic relatedness between target and distractor does exert an effect on RTs, and this effect is facilitatory. We make three points on the basis of this finding.

Firstly, the result shows that in the WWI task word reading is not completely immune from effects due to the semantics of the distractors.

Secondly, semantically related distractors facilitate target reading aloud compared with unrelated distractor, a result that is in sharp contrast with the effect of semantically related distractors in the PWI task, where such distractors exert an *interfering* effect. This asymmetry between the direction of the effects in the WWI and PWI task can be accounted for in terms of the processing differences between word reading and picture naming, namely the ease with which phonological representations are activated (La Heij et al., 1990). As argued above, in reading aloud the phonology of a written word is directly activated from its orthography; the activation of semantics from print goes in parallel with the activation of phonology from print rather than constituting a mandatory step in the activation of phonology from print (Coltheart et al., 2001). In contrast, in picture naming the activation of the semantics is a mandatory step toward the activation of the phonology (see Mulatti, Peressotti, Job, Saunders, & Coltheart, 2012; Mulatti et al., 2010; Roelofs, 2004), and the activation of the phonology follows a step of lemma retrieval (Ayora, Peressotti, Alario, Mulatti, Pluchino, et al., 2011; Levelt et al., 1999) where semantically related distractor exert their interfering effect. Thus, the process of mapping semantic representations to phonological representations has a different role in the task of reading aloud with respect to that of picture naming, and it is to the different roles of this process that the asymmetry of the semantic relatedness effects in between the WWI and PWI task can be ascribed.

Thirdly, and most crucially, the presence of a facilitatory semantic relatedness effect suggests that by the time the activation of the target's orthographic representation starts, the process of deactivation and its propagation have not set to zero the activation of the semantic units. Thus, if target and distractor are semantically related, the semantic representation of the target will be partly activated. This partial activation of the target semantic units contributes to the processing of the target.

General Discussion

The goals of this work were, first, to develop an empirically driven model of how attentional filtering works when two visual stimuli, one a target and the other a distractor, are simultaneously presented (as we noted earlier, the development of such a model requires some form of solution to a perennial problem in cognitive psychology, the biding problem) and, second, to use the WWI task to test that model. To that end, we designed four WWI experiments, each aimed at testing a specific prediction of the model we have proposed.

We need not reiterate the model here, since it is fully described in an earlier section of this paper ("The model"), so we simply note that in developing the model, we addressed four distinct theoretical issues which naturally follow from what is required for successful performance of the WWI task:

(a) A mechanism needs to be proposed that links relevant perceptual feature of the stimulus (in the case of the WWI, the location of the stimulus) to the nominal identity of the stimulus, i.e. its lexical representation. Only once the positions and the identities of the stimuli are correctly bound can the system know what to respond to and what to ignore.;

(b) Since two stimuli are presented, the second issue to be addressed is how the visual, pre-categorical representations of the stimuli first contact the information stored in memory. The stimuli are words, so, the problem here is how the letters comprising two simultaneously presented words are activated.;

(c) Since, again, two stimuli are presented and since these stimuli are words, a further issue to be addressed is the relative dynamics of activation of the corresponding orthographic and phonological lexical representations.

(d) If the lexical representations of the stimuli have been activated at a given time, then their semantic representations should also have been activated, and so an account needs to be offered as to how the semantic representation of the target and the semantic representation of the distractor interact.

Our model is explicit enough that it offers answers to all four of these questions, and also explicit enough to generate numerous predictions. Our four WWI experiments provided support for these predictions, and hence the empirical work we report offers strong support for the model.

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Table 1. Experiment 2: mean RTs in milliseconds (RTs) and percentage of errors (E%) according to condition.

	Distractor Frequency				
	High Frequency		Low Frequency		
Target Frequency	RTs	%E	RTs	%E	Difference (RTs)
Low Freq.	671	0.8	682	1.0	-11
High Freq.	652	0.7	662	1.0	-10
Difference	19	0.1	20	0.0	

Table 2. Experiment 3: mean RTs in milliseconds (RTs) and percentage of errors (E%) according to condition.

	Distractor Type				
	Word		String of # marks		
Target Case	RTs	%E	RTs	%E	Difference (RTs)
AlTeRnAtEd	736	1.1	699	1.0	-37
same	699	0.9	643	0.9	-56
Difference	37	0.2	56	0.1	

Table 3. Experiment 4: mean RTs in milliseconds (RTs) and percentage of errors (E%) according to condition.

Semantic Relation	RTs	%E
Unrelated	672	0.5
Related	643	0.4
Difference	29	0.1