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INITIAL EMBEDDED WORDS CAN FACILITATE THE RECOGNITION OF THEIR CARRIER WORD, BUT NOT ACCORDING TO TRACE-LIKE MODELS

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ABSTRACT

This theoretical article explores how initial embedded words can facilitate the recognition of their carrier, first in simulations with TRACE, second in exposing new conceptions of word recognition. Simulations with TRACE were used for testing if lexical resonance implemented in TRACE, and if activation transfer from the embedded word to the carrier, suggested by Luce and Lyons (1999), could be candidate mechanisms. These simulations proved that none of these two mechanisms explain the facilitation phenomenon. Therefore, two alternative models of word recognition were developed, LML and LEXSS. LEXSS was tested in simulations and its predictions were confronted to human behavior measurements. Results show that LEXSS predicts adequately human behavior, implying that it has some psychological validity.

Key words

Embedded word, Facilitation, Simulation, TRACE, LEXSS

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Introduction

Previous observations reported that non-morphological initial lexical embeddings, like “cough” in “coffee”, induced a faster recognition of their carrier word (coffee), compared to control words without initial lexical embedding (for instance “sugar”). This phenomenon was observed in French (Lachaud, 2005) and in English (Luce & Lyons, 1999; Taft & Forster, 1976), with isolated written words (Lachaud, 2005; Lachaud & Kerzel, 2007; Taft & Forster, 1976) and isolated spoken words (Lachaud, 2005; Luce & Lyons, 1999), in experiments using lexical decision task (Lachaud, 2005; Lachaud & Kerzel, 2007; Luce & Lyons, 1999; Taft & Forster, 1976), the shadowing task (Luce & Lyons, 1999), and non-linguistic auditory target detection task (Lachaud, 2005).

The theoretical framework proposed by psycholinguistics do not provide a valid explanation of this facilitation effect (personal communications: Dr. J. Elman (December 2005); Dr. S. Grossberg (December 2006); Dr. J. McClelland (December 2005); Dr. J. McQueen (May 2005)). Spoken words starting with lexical embedding are supposed to be more difficult to recognize than words without initial lexical embedding because of increased lexical confusability at early stages of word recognition, resulting in lexical competition. Lexical competition, on its turn, increases computational demands and the amount of time for resolving lexical conflicts.

Lexical statistics, however, reveal some inconsistency between the organization of human lexicons and the hypothesized consequences of lexical competition on word recognition. Most words in a given human language contain at least one embedded word. Therefore, most words would be difficult to recognize because of lexical competition. The case of English is eloquent, with approximately 98% of words containing a smaller word (Cutler, McQueen, Jansonius, & Bayerl, 2002), a high amount of which are initially embedded. 50.5% of polysyllabic English words also have a first lexical syllable (Davis, 2000). This percentage drops to 27% if morphological embeddings are deducted, implying that more than one polysyllabic English word out of four has a semantically unrelated lexical first syllable. Because this ratio is an underestimation (not counted: words which two first syllables form a word and words starting with a lexical sequence of phonemes not corresponding to the first syllable or the first two syllables), the lexical processor would have difficulties recognizing more than one fourth of English polysyllabic words.

Other statistics for French (Lachaud, 2005), which did not parted derivational morphology cases from non-morphological cases as Davis did, showed that 2.3 more words start with a lexical first syllable compared to those starting with a non-lexical first syllable. In addition, French speakers use 9.4 times more frequently words starting with a lexical syllable than words starting with a non-lexical syllable. Ratios fall respectively to 1.2 and 4.9 if the end of words is considered instead of word beginning. Lexical syllables are 1.3 more frequent at word beginning than at word end, and non-lexical syllables are 1.5 less frequent at word beginning than at word end. This asymmetrical organization not only implies a preferential position of syllabic lexical embeddings at the beginning of words, but also a preferential use of words with syllabic initial lexical embeddings, compared to words with a final syllabic lexical embedding or compared to words with no syllabic lexical embedding.

These statistics from English and French raise a question about evolutionary aspects of language: why would lexicons have developed with a higher lexical superimposition rate at word beginning if this configuration was making lexical processing more difficult, was increasing computational demand, and was increasing the risk to confuse words? In other words, why would organizations increasing the risk to impair communication efficiency would have developed? Wouldn’t have lexicons containing more words with final lexical embeddings been preferred to avoid creating confusion during the early stages of communication? Preference for lexical embeddings at word beginning may reveal that words tended to be created from existing words, through the rules of morphology as well as through non-morphological processes. This distribution may also suggest that initial lexical embeddings are useful to lexical processing rather than a hindrance. Put together with experimental results cited at the beginning of this introduction, lexical statistics reinforce the plausibility of an exotic hypothesis: initial lexical embeddings could play a positive role on word recognition by facilitating it.

Mechanisms causing this facilitation are however unknown, driving researchers to excitement and high speculation, and, sometimes, to arbitrary and authoritative denial. Before suggesting two new conceptions of word recognition processing, the impact of two known mechanisms on word recognition will be explored in simulations, as both are possible candidates for producing a facilitation effect. The first mechanism, lexical resonance, was studied by Grossberg in the neural tissues and modeled by this author (Carpenter, Grossberg, & Rosen, 1991; Grossberg, 1976; Grossberg & Stone, 1986). It was also implemented in TRACE as a positive feedback from lexemes to phonemes (McClelland & Elman, 1986). Lexical resonance is considered as a way to improve word recognition through sublexical reinforcement via a feedback loop between lexical and sublexical levels. The second mechanism is based on the activation transfer hypothesis suggested by Luce and Lyons (1999): “the processing advantage for the word initial stimuli may come from the fact that responses are initiated on the basis of the embedded word rather than the carrier itself. Subsequent recognition of the carrier word may either inherit the processing advantage of the embedded word through some as yet unspecified mechanism, or processing may simply shift from the representation of the embedded word to the representation of the carrier with no cost in time or effort" (p. 180). A transfer of activation from the embedded word to its carrier or carriers can be seen as a priming mechanism of the carrier word by the embedded word. This priming activation could be added to the usual bottom-up activation ascending from the sublexical level. In addition to this lexical priming process, lexical competition should not occur between the lexical embedding and the carrier. If lexical competition existed, it would reduce or cancel the facilitation gain obtained from activation transfer (Luce & Lyons, 1999): "The only apparent mechanism that could have given rise to the observed effects is the simultaneous activation of initial embedded items and carrier words in the absence of strong lateral inhibition effects among activated items, at least early in the recognition process." (p. 181).

The facilitation effect of lexical resonance and activation transfer on the recognition of words starting with non-morphological embeddings was never tested systematically in simulations. It is possibly because the facilitation phenomenon described above is not yet significantly documented. Because it is not documented enough, researchers continue to think, from the theoretical perspective in their field, that it is absurd to ever think that initial embedded words could facilitate the recognition of carrier words. Using the TRACE model of speech perception (McClelland & Elman, 1986), also referred to be a model of spoken word recognition (Frauenfelder, 1996; Frauenfelder & Peeters, 1998), the current study shows that it is actually impossible to obtain a similar facilitation as observed in humans with resonance and activation transfer. TRACE is a major contribution to the field of spoken word recognition in psycholinguistics and is still a reference today. Three reasons justified its use in this study instead of other models of spoken word recognition. The first reason is theoretical. Because TRACE formulates very clear processing explanations and behavioral predictions in case of lexical embeddings (McClelland & Elman, 1986), it was possible to isolate a set of factors influencing the recognition speed of a word containing an embedded word, and to manipulate them in experimental designs. The second reason is the psychological validation of TRACE. Theoretical assumptions and predictions of TRACE are easily testable and numerous experimental studies measuring human behavior confirmed its principles, crediting the model with some amount of psychological validity. The third reason is practical. TRACE being made public in software implementation can be used to run simulations. This is not the case with other interesting models. The jTRACE implementation of TRACE (Strauss, Harris, & Magnuson, 2007) was preferred to the original TRACE version because it includes a parameter for lexical frequency allowing to model priming effects.

Previous works purposely tested TRACE in simulations, in order to provide a listing of its behaviors under different constraints (Frauenfelder & Peeters, 1990, 1998; McClelland & Elman, 1986). Although its reaction with lexical embeddings was already documented in these articles, testing was never conceived to answer the research questions tackled here. Baseline conditions and a complete homogeneous testing were needed, implying that new simulations had to be run.

The current set of simulations will manipulate five factors. All five factors influence the amount of lexical competition exerted on the lexeme of a stimulus word. More competition implies an increased difficulty to recognize the stimulus word, which translates in time as longer recognition durations. The first factor that will be manipulated is the amount of lexical resonance between words. TRACE states that a lexeme receives facilitation from the lexicon through a resonance phenomenon implemented as a positive feedback from lexemes to phonemes. Consequently, the recognition of a carrier word would benefit from an embedded word and from dense lexical neighborhoods through resonance. The second factor is the presence of a lexical embedding. TRACE states that a configuration of lexical embedding is adverse for recognition because of another mechanism, competition between the carrier word and the embedded word.

Competition delays the recognition of the carrier word compared to control words without lexical embedding. The third factor is the amount of competition received by the lexeme of the carrier word from the lexicon, formalized in the concept of neighborhood density. In this study, neighborhood density will be formalized in a restrictive manner, as the amount of words sharing the same lexical embedding at the same position. TRACE states that the competition on the carrier word will be more intense in a dense neighborhood (i.e. more words sharing the same lexical embedding at the same specified position) than in a sparse neighborhood (i.e. little number of words sharing the same lexical embedding at the same specified position). Words from dense neighborhoods will be more difficult to recognize than words from sparse neighborhoods. The fourth factor is the overlapping rate between the embedded word and its carrier. This overlapping rate is computed from the amount of phonemes of the carrier word that correspond to the embedded word, translated in percentage. TRACE states that the amount of lexical competition will increase with overlapping rate. Stimuli with an important overlapping rate will be more difficult to recognize than stimuli with a small overlapping rate. The fifth factor is the position of the lexical embedding in the carrier word. TRACE states that lexical competition generated by a lexical embedding will be more important at the beginning than at the end of the carrier word. Because the lexeme of an initial embedded word is activated simultaneously with the lexeme of the carrier word, the recognition process starts with a full force competition between the two lexemes until the sequence of phonemes makes them distinct. Once the two lexemes are distinct based on the input, competition continues to go on until a word among the alternatives reaches some activation threshold defining conscious recognition, a process which delays recognition. It is not the case with a final lexical embedding, where the lexeme of the embedded word starts activating when the lexeme of the carrier word is almost fully activated. Because of this delay, the lexeme of the embedded word is highly inhibited by the lexeme of the carrier word, while the lexeme of the carrier word gets little influenced by the lexeme of the embedded word. Consequently, words starting with a lexical embedding will be more difficult to recognize than words ending with a lexical embedding.

Two sets of simulations explored the benefits of resonance and activation transfer on the recognition of words containing lexical embeddings. The first set of simulations tested the role of lexical resonance by modulating TRACE's parameters. This first set of simulations used Factors 1 and 2, respectively the amount of resonance between words and the presence of a lexical embedding. The second set of simulations tested the hypothesis of activation transfer between lexemes through a procedure not implemented in TRACE, which will be described later. The second set of simulations used Factors 3, 4 and 5, respectively the amount of competition received from the lexicon, the overlapping rate, and the lexical embedding position.

In the discussion part of the article, two alternative conceptions of the mental lexicon and recognition process will be presented in order to account for behavioral data measured in humans: the Layered Mental Lexicon (LML) and the LEXical Superimposition Structure (LEXSS). The plausibility of these two conceptions will be demonstrated with examples, results from mathematical simulations with LEXSS, and LEXSS predictions in relation with behavioral data measured in humans.

First set of simulations: Effect of resonance in TRACE

The first set of simulations tested whether facilitation could happen in TRACE through lexical resonance. Resonance existing between lexemes via a positive feedback loop with the sublexical layer is supposed to enhance the recognition of a word (McClelland & Elman, 1986). In case of lexical embeddings, the carrier word should receive facilitation from its embedded word(s) through this resonance mechanism, the same way that the embedded word(s) would. However, any increase in lexical activation will also increase lexical competition through inter-lexemes inhibitory links. Because, lateral inhibition may counter facilitation produced from resonance, it seems unlikely that resonance could be the cause of facilitation observed in humans. However, getting facilitation through resonance might be a matter of fine-tuning between positive feedback and lateral inhibition, which needs to be tested systematically. The goals of this first set of simulations are: first to show that without modifying TRACE parameters, resonance does not produce facilitation, for it is compensated by competition (First hypothesis); second, to show that resonance, if amplified to override competition, brings TRACE to lose its lexical discriminative properties in case of lexical embedding (Second Hypothesis). Therefore, this first set of simulations aims at demonstrating that the mechanism of lexical resonance as set in TRACE can not be the mechanism behind the recognition facilitation of words containing initial lexical embeddings.

Materials and methods

Two series of simulations were run in the first set of simulations. The first series of simulations tested the first hypothesis. The second series of simulations tested the second hypothesis.

The first series contained four simulations. Each simulation was defined by combining one of two parameters sets with one of two lexicons. Two sets of parameters were used to implement Factor 1 (resonance). The default set of parameters in jTRACE,[1] was used to allow resonance in the system. This set is referred to as “Pr”. A control set of parameters referred to as

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[1] Input noise and stochastic 0; spread scale 1, min -0.3, max 1; fslices 66, delta input 6, nreps 1; slices per phoneme 3; α: [if] 1, [fp] 0.02, [pw] 0.05, [pf] 0, [wp] 0.03; γ: [f] 0.04, [p] 0.04, [w] 0.03; Decay: [f] 0.01, [p] 0.03, [w] 0.05; Fetspread: pow 3, voc 6, dif 6, ocu 9, gra 9, voi 3, bur 3; Rest: f -0.1, p -0.1, w -0.01.

"Pc" was used to prevent resonance from occurring in the system. All parameters in Pc were the same as in Pr, except αwp, the positive feedback from words to phonemes, which was set to 0.

Two lexicons were created based on Factor 2 (initial lexical embedding vs. no initial lexical embedding), in order to oppose a situation where lexical resonance can occur (Test lexicon) with a situation where no lexical resonance can occur (Control lexicon). Both lexicons contained a restricted amount of four "words", in order to control various parameters. These words were not English words but non-words built from the set of phonemes existing in jTRACE. The design of words and lexicons was following the purposes of the study. The stimulus word, identical in the two lexicons, was five phonemes long (/garuS/). It had three competitors, respectively composed of two, three, and four phonemes, which differed between the two lexicons. In the Control lexicon, the stimulus word shared no phoneme with the three "competitors", but the three "competitors" shared embedding relations between themselves in such a way that the word of two phonemes started the word of three phonemes, which itself started the word of four phonemes. This organization allowed separating words in two distinct ensembles in order to avoid any resonance between the stimulus word and the three "competitors". In the Test lexicon, on the contrary, resonance could organically occur as all four words share embedding relations. The Test lexicon was design to produce a maximal resonance on the stimulus word (the word of two phonemes started the word of three phonemes, which started the word of four phonemes, which started the stimulus word. Compared to the Control lexicon, the Test lexicon has all its words grouped into the same ensemble). Table 1 gives the content of each lexicon.

Table 1: Lexicons used in the first and second series of simulations from the first set

Lexicon conditions	Lexicon content

		Stimulus	Competitors
Control	No lexical resonance	garuS	si, sit, sit^
Test	Lexical resonance	garuS	ga, gar, garu

Because no resonance and no competition can occur on the lexeme of the stimulus word in the control lexicon, the behavior of TRACE should be identical with both the “Pc” and the “Pr” parameters sets when using the Control lexicon. On the contrary, the recognition time of the stimulus word should be longer with the Test lexicon than with the Control lexicon because of lexical competition. This would be specifically the case with the “Pc” set of parameters, while lexical resonance could counter lexical competition fully or partly in case the “Pr” set of parameters is applied. Notice that no mechanism allows hypothesizing that faster recognition of the stimulus (compared to the control) should be observed at any time. Therefore, the design of this first series of simulations will measure the effect of lexical competition and will determine to what extent it can be reduced by lexical facilitation.

The second series of simulations in the first set of simulations contained 6 simulations. The two artificial lexicons from the first series were used with three sets of parameters: P0 the Control set, and P1 and P2 the Test sets (Table 2). P0 is the default set of parameters of jTRACE. It is therefore the same set as Pr used in the first series of simulations, though named differently as it plays now a control role. Test sets of parameters were obtained by varying the following three parameters: (a) the force of bottom-up and top-down facilitatory links between phonemes and lexemes, (b) the force of lateral inhibitory links between lexemes, and (c) the phoneme and word units’ remanence (decay). Constraints for defining P1 and P2 were to maximize the force of facilitatory links, to minimize the force of inhibitory links, to maximize the inter-sets difference, and to avoid transforming TRACE into an oscillator. Indeed, parameters had to be kept in the very small window preserving the ability of TRACE to converge to the solution. Parameters combination is numerous, but only a few of them allow keeping TRACE functioning. The selection procedure was first to increase parameter (a) from its P0 value without modifying any other parameter. As this manipulation resulted in a complete loss of discrimination in the system, all lexemes being fully activated, other parameters were adjusted to get rid of this undesired general activation: parameters (b) and (c) were augmented. Finally, to get an equivalent amplitude difference in the behavior of TRACE between P0 and P1 on one hand, and between P0 and P2 on the other hand, the "Resonance/(Inhibition + Decay)" ratio, given in Table 2, was set to differ with approximately the same amplitude (P1 - P0 = +0.17; P2 - P0 = -0.19). The series of simulations for adjusting P1 and P2 will not be presented. P0, P1 and P2 are given in Table 2.

Table 2: Sets of parameters used in the second series of simulations

	P0	P1	P2
α pw	0.05	0.2	0.15
α wp	0.03	0.05	0.05
γ w	0.03	0.08	0.08
Decay p	0.03	0.1	0.15
Decay w	0.05	0.1	0.15
R/(I + D) Ratio	0.72	0.89	0.53

<u>Note.</u> α activation. γ inhibition. p phoneme. w word. R/(I + D) Ratio "Resonance/(Inhibition + Decay)" ratio.

No recognition time differences between the three sets of parameters should be visible with the Control lexicon, or very minor ones as other factors than resonance were also adjusted in various sets of parameters. On the contrary, with the Test lexicon, the P1 and P2 sets should drive to facilitate recognition of the stimulus compared to the P0 control set because of an increased resonance.

In all simulations of the first and second series, TRACE was stimulated with the “word” /garuS/. TRACE computed until it stopped on its own after 179 computing cycles. The amount of computing cycles needed to recognize the stimulus word was determined with Equation 1, adapted from the R. D. Luce’s choice rule given in Frauenfelder and Peeters (1998).

$$f(x) = EXP(x)_{stimulus} \Big/ \sum_{1}^{n} EXP(x)_{competitor\ n} \qquad \text{Eq 1}$$

where x is the probability level of each one of the n lexemes in the lexicon, EXP is the exponential function.

A word was considered recognized if the value given by Equation 1 was above 1 (threshold at which the activation level of the stimulus lexeme becomes superior to the activation level of any competitor), and if the evolution of f(x) was not decreasing through cycles. If f(x) started above 1 but was decreasing, the moment of recognition was not set at the beginning of the simulation, but at the inflexion point of f(x). Recognition time was measured as the number of computing cycles (required for f(x) to reach 1 or the inflexion point) converted in milliseconds (1 computation cycle analyzing 25 ms of speech is approximately equivalent to 25 ms of computing duration in humans according to (McClelland & Elman, 1986)).

Results

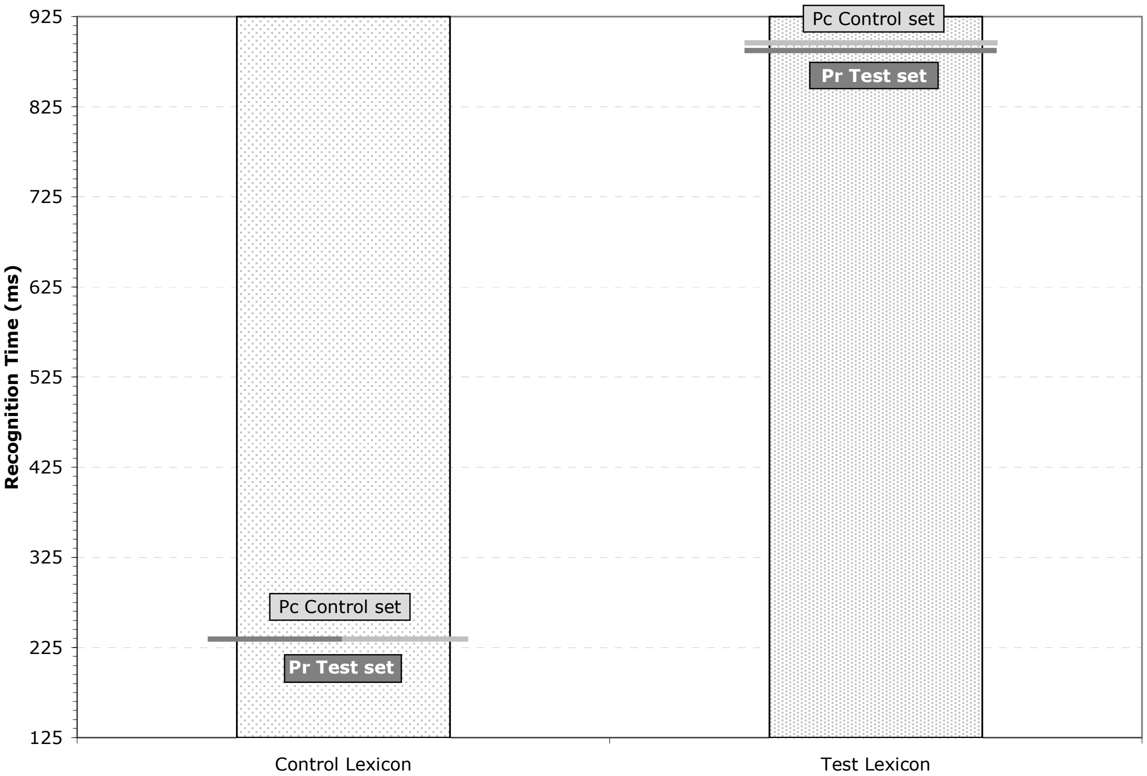
Table 3 and Figure 1 show results obtained from the first series of simulations.

Table 3: Recognition time (ms) of the stimulus word depending on lexical resonance (lexicon * parameters) in the first series of simulations

		Pc Control set	Pr Test set	Δ
Control	No resonance	238	238	0
Test	Resonance	895	890	-5
	Δ	+657	+652	-5

Note. Δ difference between factor levels.

Figure 1: Duration needed for recognizing a stimulus word depending on lexical resonance (lexicon * parameters) in the first series of simulations



As predicted, the Control lexicon did not allow any recognition latency difference between the Pc control set and the Pr test set of parameters. On the contrary, the Test lexicon allowed a minor fluctuation of -5 ms due to resonance, appearing with the Pr set of parameters compared to the no resonance Pc set of parameters.

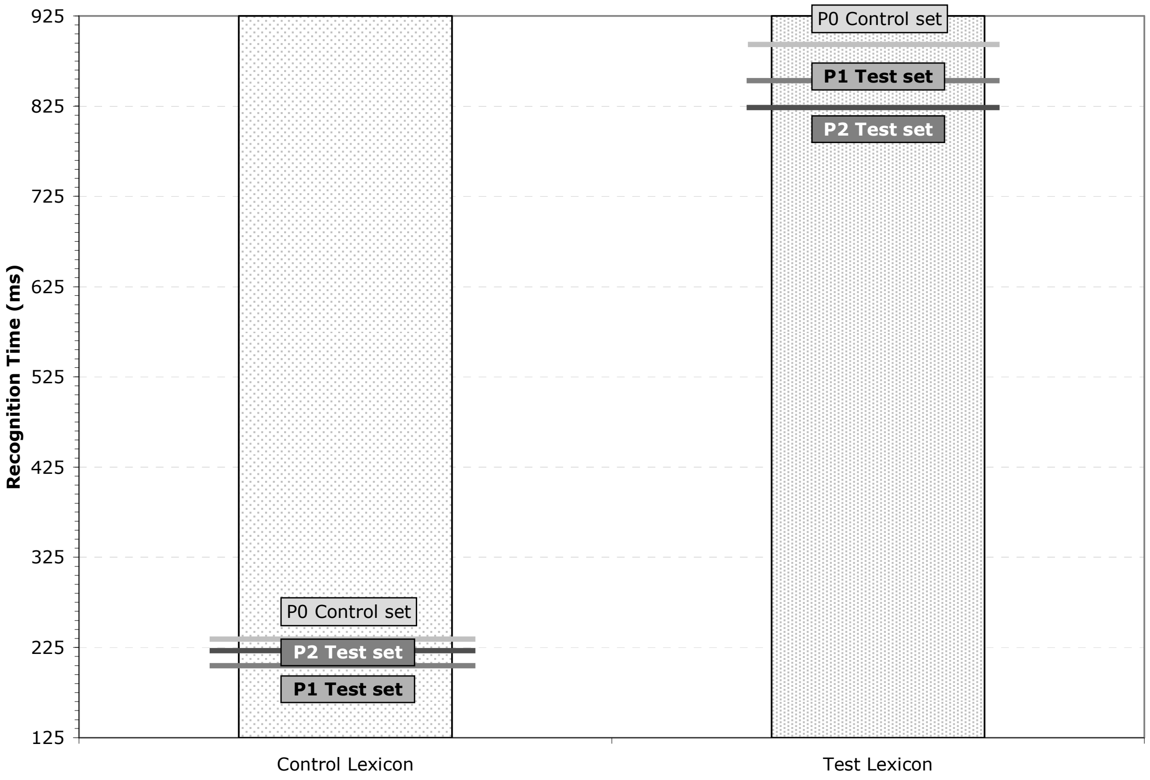
Table 4 and Figure 2 show results obtained from the second series of simulations.

Table 4: Duration (ms) needed for recognizing a stimulus word depending on lexical resonance (lexicon * parameters) in the second series of simulations

		P0	P1 Test set		P2 Test set	
		Control set	RT	Δ	RT	Δ
Control	No Lex. resonance	238	210	-28	225	-13
Test	Lexical resonance	890	850	-40	828	-62
	Δ	+652	+640	-12	+603	-49

Note. RT recognition time for the stimulus, in ms. Δ difference between factor levels (P1 - P0; P2 - P0; Test - Control).

Figure 2: Duration needed for recognizing a stimulus word depending on lexical resonance (lexicon * parameters) in the second series of simulations



Simulations with the Control lexicon showed that parameters variation could improve the recognition speed of TRACE, though minimally. The recognition of the stimulus word was faster with the P1 (210 ms) and P2 (225 ms) sets of parameters compared to the P0 control set of parameters (238 ms). The average gain, considering P1 and P2 over P0, was -20 ms. Simulations with the Test lexicon showed that the advantage of the P1 (850 ms) and P2 (828 ms) sets of parameters was maintained compared to the P0 control set (890 ms). The average gain, considering P1 and P2 over P0, was -51 ms. Therefore, resonance, which was only possible with the test lexicon, caused the 31 ms gain difference between the Control and Test lexicons. However, the effect of lexical competition compensated largely this resonance gain: the stimulus was recognized, on average, +532 ms slower with the Test lexicon (lexical competition) than with the Control lexicon (no lexical competition).

Discussion

The first series of simulations testing if resonance in TRACE was a mechanism of sufficient amplitude to cause significant facilitation showed that it was not the case. The positive top-down feedback from words to phonemes has little impact on the recognition of a word containing an initial lexical embedding compared to the magnitude of lexical competition. Consequently, lexical resonance, as it is built and parameterized in TRACE, cannot explain the lexical facilitation measured experimentally in human beings.

The second series of simulations, testing if a modulation of TRACE parameters could increase the amplitude of facilitation to such an extent that it compensates the effect of lateral inhibition, showed that better performances could be obtained with a fine-tuning of the system compared to the default setting. The facilitation due to resonance was however of insufficient amplitude to override lexical competition.

In conclusion, the first set of simulations shows that lexical resonance alone cannot explain the facilitation observed in human beings processing words with an initial lexical embedding. Other mechanisms must be considered.

Second set of simulations: Effect of lexical priming in TRACE

According to Luce and Lyons (1999), the lexeme of a word embedded at the beginning of carrier words could transfer its activation to all the lexemes of these carrier words when the uniqueness point of the embedded word is reached. It would do so without conflicting with its carrier words, or without conflicting anymore, through lexical competition. This transfer mechanism will be referred to as "global priming" in the current study. Benefiting from an additional source of activation, the carrier words' lexemes would reach the recognition threshold faster than words with no initial lexical embedding. This would happen in the case where the embedded word only exists in one carrier. Indeed, in theory, global priming should hardly facilitate the recognition of any of its carrier words (in the case an embedded word exists in more than one carrier words) because of lateral inhibition between them. In this case, lexical competition would take the form of an adverse "gang effect". This gang effect being reinforced by global priming might finally make global priming a hindrance for recognition in most of the cases of initial lexical embeddings. Consequently, in order to avoid reinforcing any gang effect, activation transfer must occur specifically from the embedded word's lexeme to the target carrier word's lexeme, which will be referred to as "targeted priming" in this study. It is however still unclear if targeted priming will allow overriding the influence of lexical competition. To test if these two priming mechanisms, i.e. global priming and target priming, could generate facilitation and compensate lexical competition, the second set of simulations was run.

Materials and Methods

The second set of simulations consisted in 32 simulations divided in four series of 8 simulations, each one of the 8 simulations in a series using a different lexicon.

Factors and Lexicons

Eight artificial lexicons were created by crossing three of the five factors described above, Factors 3, 4 and 5. Each factor had two levels. Factor 3 or neighborhood size of the carrier word was sparse (1 word) vs. dense (5 words). Factor 4 or length of the stimulus carrier word was short (3 phonemes) vs. long (5 phonemes). Factor 5 or position of the lexical embedding in the stimulus word was at the beginning vs. at the end.

All lexicons contained one embedded word and one carrier stimulus word. Half of lexicons additionally contained 4 competitors forming a gang against the carrier stimulus word. The embedded word was the same in all lexicons, while the stimulus word varied. Table 5 presents the lexicons' content depending on three factors.

Table 5: Characteristics and content of the lexicons used in the second set of simulations

Factor 3 Neighborhood size	Factor 4 Stimulus carrier length	Factor 5 Embedding Position	Lexicon		
			Emb	Stim	Competitors
Sparse	Short	Beginning	ba	bat	
		End	ba	tba	
	Long	Beginning	ba	balis	
		End	ba	lisba	
Dense	Short	Beginning	ba	bat	bal, bar, bas, bag
		End	ba	tba	lba, rba, sba, gba
	Long	Beginning	ba	balis	bar^t, bapuS, bak^r, baSut
		End	ba	lisba	r^tba, puSba, k^rba, Sutba

Factor 3. The two-word lexicons containing the embedded word and the stimulus carrier word implemented the sparse neighborhood condition. The six-word lexicons containing the

embedded word, the stimulus carrier word, and four additional competitors, implemented the dense neighborhood condition. Competitors had all the same amount of phonemes as the stimulus carrier word, had the embedded word located in the same position than in the stimulus carrier word, and did not share any other phoneme with the stimulus carrier word than the two phonemes composing the embedded word. Within-gang competition could not be limited to the lexical embedding. Because of a restricted set of phonemes in jTRACE, long competitors had to share, two by two, additional phonemes (see Table 5), which increased within-gang competition. Consequently, the gang effect on the stimulus word was reduced as the activation level of competitors was reduced. Nevertheless a gang effect still existed with high enough intensity to allow a successful demonstration.

Factor 4. Stimulus carrier length modified lexical confusability by varying superimposition rate between the carrier word and the embedded word. It was set at 66.7% in the short condition vs. 40% in the long condition.

Factor 5. Location of lexical embedding in the carrier word varied competition intensity between the carrier word and the embedded word through processing dynamics. Lexical competition was strong with initial lexical embeddings vs. weak with final lexical embeddings. The stimulus word was built accordingly, with an embedded word at the beginning vs. at the end, while the sequence of phonemes corresponding to the non-embedding part of the carrier was kept identical (respectively at the end vs. at the beginning -- see Table 5).

Simulating Priming in TRACE

Simulating priming in TRACE was achieved through a manipulation of “Frequency”: (1) by modulating the resting level of lexemes (“frequency effect”) according to the simulation design (see Table 6), and (2) by setting the parameter “frequency resting level” to 0.06 to allow frequency effects, as suggested by Dahan, Magnuson and Tanenhaus (2001).

Procedure

All simulation parameters were left to the default values of jTRACE (see note 1), except “frequency resting level”, which was varied according to the experimental design. The procedure is now going to be described. Each one of the eight artificial lexicons was used in four simulations. In the first simulations, the frequency of all lexemes was set to zero. The embedded word “BA” was the stimulus. The activation level of its lexeme was measured at the moment of its selection as defined by Equation 1 and following the procedure detailed for the first set of simulations. The obtained value corresponded to the “priming value” subsequently used in second and third simulation series. In the second simulation series, activation level of all lexemes was set to the priming value of lexeme /ba/, as measured in the first simulation series. Technically, it means that all lexemes were given some activation level before any stimulus occurs. This corresponded to the “global priming” condition. In the third simulation series, only the activation level of the stimulus word was set to the priming value. This corresponded to the “Targeted priming” condition. Second and third simulation series measured the time needed by TRACE to recognize primed stimulus words following the same measuring procedure detailed for the first set of simulations. A fourth simulation series measured the time needed to recognize the stimulus word when no priming occurs (all lexeme frequencies were set to 0). This corresponded to the “Control” condition. Respectively, Simulations 1 to 4 are respectively referred to as “Prime activation level”, “Global”, “Targeted”, and “Control”. Table 6 provides the simulation design, showing the repartition of simulations depending on the lexical conditions.

Table 6: Repartition of 32 simulations according to simulation design

Stimulus length		Short		Long	
Position of BA in the carrier		Beginning	End	Beginning	End
Stimulus		BAT	TBA	BALIS	LISBA
Neighborhood	Sparse	1, 9, 17, 25	3, 11, 19, 27	5, 13, 21, 29	7, 15, 23, 31
	Dense	2, 10, 18, 26	4, 12, 20, 28	6, 14, 22, 30	8, 16, 24, 32

Note. 1 to 8 is Prime activation level, 9 to 16 is Global, 17 to 24 is Targeted, and 25 to 32 is Control.

Results

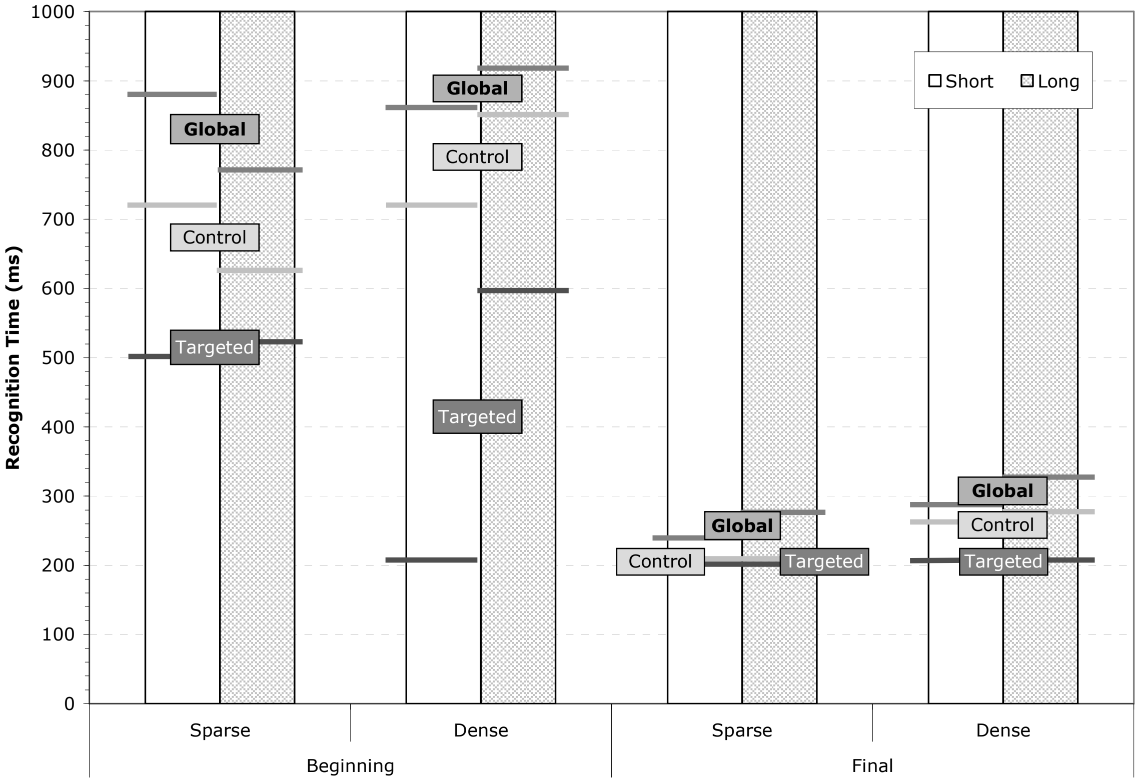
Table 7 and Figure 3 show recognition times for stimulus carrier words depending on lexical factors and priming conditions.

Table 7: Recognition times (ms) of the stimulus carrier word, depending on lexical factors (Neighborhood, Stimulus length, Embedded position) and priming conditions (Control, Global and Targeted).

Lexical Factors				Priming Conditions				
Neighborhood	Stimulus length	Embedding position	Stimulus	Control	Global		Targeted	
					RT	Δ	RT	Δ
Sparse	Short	Beginning	BAt	713	880	+167	500	-213
		End	tBA	200	245	+45	200	0
	Long	Beginning	BAlis	625	775	+150	525	-100
		End	lisBA	200	305	+105	200	0
Dense	Short	Beginning	BAt	705	860	+155	200	-505
		End	tBA	268	295	+27	200	-68
	Long	Beginning	BAlis	850	923	+73	600	-250
		End	lisBA	280	325	+45	200	-80

Note. RT recognition time of the stimulus, in ms. Δ time difference between a priming condition and the control condition.

Figure 3: Effect of lexical embedding on the recognition speed of a stimulus carrier word, depending on lexical factors (Neighborhood, Stimulus length, Embedded position) and priming conditions (Control, Global and Targeted)



Control condition (no priming): Words in dense lexical neighborhoods (526 ms) were recognized slower (+91 ms) than words in sparse neighborhoods (435 ms). Short words (472 ms) were recognized faster (-17 ms) than long words (489 ms). Words with an initial lexical embedding (723 ms) were recognized slower (+486 ms) than words with a final lexical embedding (237 ms).

Global priming: the average recognition times (576 ms) were 96 ms slower in the Global condition than in the control condition (480 ms). Compared to the control condition, words in dense neighborhoods (+75 ms) had a smaller (-42 ms) increase of recognition duration than words in sparse neighborhoods (+117 ms). Short words (+99 ms) had increased recognition duration close to long words (+93 ms). Words with initial lexical embeddings (+136 ms) had a greater recognition duration increase (+80 ms) than words with final lexical embeddings (+56 ms).

Targeted priming: the average recognition times (328 ms) were 152 ms faster in the Targeted condition than in the Control condition (480 ms). Words in dense neighborhoods (-226 ms) were facilitated more (-148 ms) than words in small neighborhoods (-78 ms), although recognition times were still 56 ms longer in the sparse condition (356 ms) than in the dense condition (300 ms). Short words (-197 ms) benefited more from priming (-89 ms) than long words (-108 ms). Likewise (-230 ms) for words with initial lexical embedding (-267 ms) compared to words with final lexical embedding (-37 ms). Short words with an initial lexical embedding (-359 ms) benefited substantially more from priming (-184 ms) than did long words with an initial lexical embedding (-175 ms), while the impact was approximately of same magnitude for words with final lexical embeddings (respectively -34 and -40 ms).

Discussion

The second set of simulations revealed that global priming is not the best solution for explaining the facilitation caused by non-morphological initial lexical embeddings in humans' lexical processing. Spreading of activation to a set of lexical competitors increases any gang effect on the target lexeme, causing performance degradation instead of performance improvement. Similarly, targeted priming, by specifically increasing the activation level of the stimulus lexeme, did not succeed in facilitating the recognition of words beginning with a lexical embedding compared to words that ended with a lexical embedding, despite identical or faster reaction times when compared to control conditions. Average recognition times for words carrying an initial embedding (456 ms) were still 256 ms slower than recognition times for words carrying a final embedding (200 ms). The conclusion to draw from these simulations is that it is impossible to reproduce the behavioral pattern observed in humans with TRACE, using the mechanism of targeted activation transfer from the embedded word's lexeme to the carrier word's lexeme. The second set of simulations therefore proves that a system using a generalized and relatively blind mechanism like lateral inhibition for lexical selection may be inexact or incomplete with reference to the natural system of word recognition. The structure of the system may be in cause rather than mechanisms themselves.

General Discussion

This study investigated if an initial embedded word could facilitate the recognition of its carrier in a model using lateral inhibition as a selection mechanism. A series of simulations were conducted with TRACE, exploring first the impact on word recognition of lexical resonance happening via a positive feedback loop from lexemes to phonemes, and second the impact on word recognition of activation transfer through priming from the embedded word's lexeme to the carrier word's lexeme. Simulations from the second set showed that it was not possible to reproduce the behavioral pattern of facilitation observed in humans. Though it was possible to improve recognition speed, lexical competition was always greater than facilitation. Consequently, it was impossible to measure faster reaction times with the initial embedding configuration, compared to the no embedding and the final embedding configurations. By showing that lexical resonance as well as blind and targeted activation transfer were not sufficient to explain facilitation caused by initial lexical embeddings, this simulation study therefore eliminated a set of possible explanations suggested by colleagues, implying that alternative explanations has now to be explored.

Alternative explanations

Reconsidering the structure of the system appeared as a promising track to follow. However, entering debate about some inconsistencies related to the lateral inhibition mechanism might be highly controversial. Actually, simulations presented in this paper as well as behavioral results from the studies of (Lachaud, 2005; Lachaud & Kerzel, 2007; Luce & Lyons, 1999), suggest that at least three restrictions on lateral inhibition must be satisfied to allow any facilitation effect by initial lexical embeddings. First, the lexeme of an embedded word, which is linked with the lexemes of all its carriers, should either prime only the lexeme of the stimulus carrier word, or lateral inhibition between lexemes should be suppressed. This first constraint is required to avoid any gang effect from all words carrying the same embedded word on the lexeme of the stimulus word. Targeted priming is a possible solution. Second, the lexeme of the embedded word should not be massively inhibited by the lexemes of its carriers. This second constraint is required to avoid any gang effect from the lexemes of the carriers on the lexeme of the embedded word, which would prevent the possibility to ever recognize a word that also exists in an embedded format. Finally, the lexeme of the carrier stimulus word should not have inhibitory relations with the lexemes of words containing the same embedded word, based on their embedded word’s part. This third constraint is required if facilitation is to be obtained in case of initial lexical embedding compared to a final lexical embedding. This set of three constraints would be easily implemented in a layered lexicon, in which the second layer implements a system of matrices encoding the relations between lexemes. Two alternatives of layered lexicons, the Layered Mental Lexicon (LML) and the LEXical Superimposing Structure model (LEXSS), are now presented and discussed.

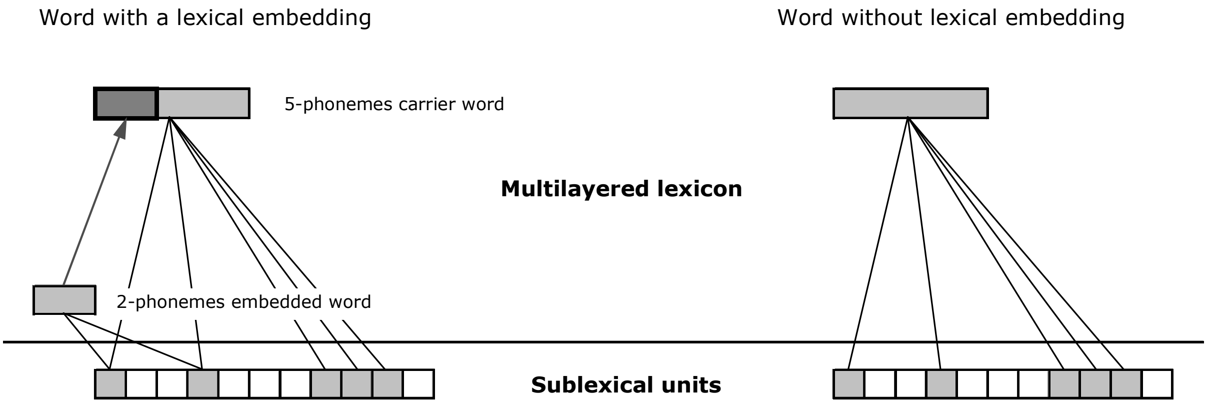
The layered Mental Lexicon (LML)

LML states that the lexicon would not be composed of a unique layer of lexical representations (as it is usually implemented in TRACE and other models of spoken word recognition), but as a layered structure hierarchically organized by increasing lexical complexity from the simplest to the most complex. Simplest one-phoneme words would form the first bottom lexical layer, distinct from the sublexical layer encoding phonemes, while the longest non-compound words would be stored in the last top layer. Each word, whatever its layer and its embedding configuration, would be linked directly to all its sublexical components through bottom-up facilitatory links. It would additionally be linked to its lexical component(s) or embedded word(s) at the corresponding previous lexical layer(s) with bottom-up facilitatory links. Within each layer, lexemes would be related through inhibitory links. The strength of such links would depend on the misalignment of shared sublexical components corresponding or not to an embedded word, on the position of this misalignment in the word, and on the amount of shared sublexical components between words. Words of same length starting with the same lexical embedding would not inhibit mutually until they start diverging because their shared sublexical components are aligned. On the contrary, misaligned shared sublexical components would cause inhibition. Therefore, in the case of lexical embeddings, two situations would exist: misaligned embeddings, and aligned embeddings. In case of misaligned misalignments, the intensity of inhibition would be inversely proportional to the misalignment. For instance, “Iceland”, “bisector” and “paradise”, three words sharing the sequence of phonemes /aɪs/ (embedded word "ice") and belonging to the same 7-phonemes layer, would not inhibit mutually with the same strength. The inhibition would be more important between "Iceland" and "bisector" than between "Iceland" and "paradise" because the misalignment of shared part "ice" is one phoneme vs. five phonemes. In case of aligned embeddings, inhibition would depend on position in the word, decreasing towards the end of the word. For instance, "spicy" and "slicer" would inhibit reciprocally more than "advice" and "entice".

Words would not be related between layers except if they share embedding relations. In that specific case only, links would be facilitatory and bottom-up oriented from the embedded word's lexeme to the carrier word's lexeme. Lexemes of embedded words would not be facilitated by lexemes of carrier words, but would not be inhibited either, giving the embedded words a chance to be recognized. Strength of interlayer links could depend on embedding position in the word, stronger for initial lexical embeddings than for final lexical embeddings. Combined with intra-layer inhibition patterns, the effect of any lexical embedding at the beginning would be highly facilitatory, gradually vanishing towards the end.

In case of initial lexical embedding, the LML structure would work as an activation concentrator, causing the carrier word to be facilitated (see Figure 4), compared to words with no lexical embedding or compared to words with a final lexical embedding. The lexeme of the carrier word (5-phonemes word in the left part of the Figure 4) receives activation from sublexical units (grey lines) and from the lexeme of a 2-phonemes embedded word (arrow). No lateral inhibition occurs between the 2-phonemes embedded word's lexeme and the 5-phonemes carrier word's lexeme. The lexeme of the carrier word receiving bottom-up activation from sublexical components and from the lexeme of the embedded word will therefore cumulate high amount of activation (dark grey). On the contrary, the lexeme of a word without lexical embedding (right part of Figure 4) only receiving bottom-up activation from the sublexical level will only cumulate activation from the sublexical layer (lighter grey).

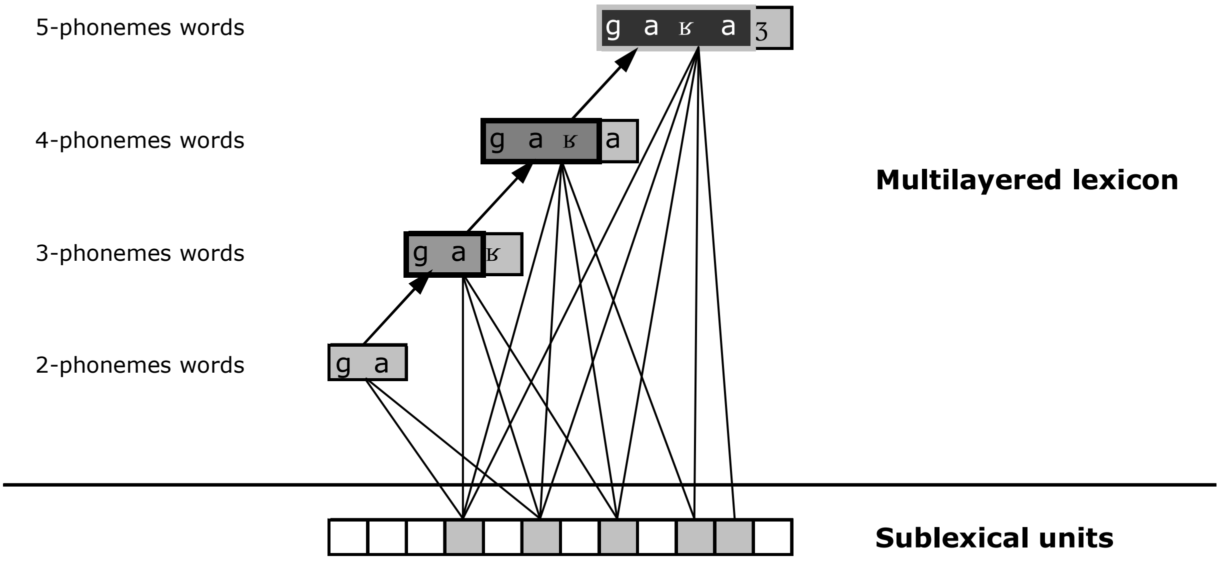
Figure 4. Activation of a lexeme in a multilayered mental lexicon, depending on the embedding configuration



Because the selection process would not be based on lateral inhibition mechanisms exclusively and because multiple activations may still occur in parallel, the system could avoid losing its discriminative abilities with bottom-up deactivation mechanisms, like postulated in Marslen-Wilson and Welsh (1978). As the uniqueness point of the embedded word is reached, lexemes of all competitors for the carrier word would be deactivated because of the mismatch between representation and input. Deactivated lexemes as well as all multiple lexical segmentation alternatives could then be stored in a buffer (in case subsequent correction is necessary) in order them to stop interfering with the target lexeme during the recognition process. As suggested in Mattys (1997), buffers may play a greater role in word recognition than accounted for in models like TRACE. Selection between multiple alternatives may specially happen in such short-term memory buffers.

It is worth mentioning that according to LML, the recognition of the carrier word will be easier in case of cascaded initial lexical embeddings compared to a single initial lexical embedding. For instance, the French word “garage” (/gaʁaʒ/, meaning garage) starts with the embedded words /ga/ (gars, meaning guy), /gaʁ/ (gare, meaning train station), and /gaʁa/ (gara, meaning (he) parked). Because of a cascaded transfer of activation from “gars” to “gare” to “gara” to “garage”, the lexeme of the word “garage” is expected to cumulate more activation from its embeddings as shown in Figure 5.

Figure 5. Process of activation concentration in case of cascaded initial embeddings: example of the word “garage”



LML is a verbal model, which may be easily specified into equations. From LML is derived a second model which was formulated in equations (see Lachaud (2005) for a draft of mathematical aspects), LEXSS.

The Lexical Superimposition Structure (LEXSS)

LEXSS is a development directly inspired from LML, implementing in a more elaborated manner the mechanisms described above, and offering some simulation possibilities. LEXSS states that no selection mechanism occurs at the lexeme level because it is too early in the process of word recognition. Therefore, no lateral inhibition between units is needed at the lexeme level. Selection occurs later and passively through multiple constraints satisfaction after a dynamic process of integration involving facilitation and inhibition. For the sake of simplification and understanding, the current version of LEXSS only models the perceptual integration of lexical information. However, its principle could be at least extended to the integration of semantic dimensions.

LEXSS assumes the existence of two supralexical layers, the first layer containing “word” matrices, one matrix per known word, the second supralexical layer containing matrices of matrices.

The first matrix layer is in charge of encoding the relations between lexemes, i.e. inhibition or facilitation, the strength of the relation between lexemes, and its directionality. It is also responsible for balancing the activation level of a lexeme by magnifying it or reducing it in a matrix, depending on matrix composition. Thanks to these processes, the matrix layer integrates various aspects of a stimulus to build a lexical percept. In LEXSS, each matrix outputs a score of activation corresponding to the perceptual vividness of a word in relation to the stimulus characteristics as well as to the lexicon structure, which depends among other factors on its lexical embedding composition. The second supralexical matrix layer organizes the lexicon at a macro level by grouping words into clusters and managing facilitatory or inhibitory relations between these clusters. Therefore, matrices can be isolated, or on the contrary, linked together to form trunk and branch structures depending on the similarity between words, the same superimposing principle existing both within a matrix and between matrices. Thanks to this meta-lexical organization, LEXSS predicts “branch effects”, like neighborhood facilitation, implying that LEXSS does not only model simple cohort phenomena. A word like “gars”, coded by a matrix embedded at the beginning of many matrices, should be recognized faster than a word of same length and same embedding structure coded by an isolated matrix. The reason why is that the links strength between nodes in a matrix is stronger due to matrices superimposition, and excitability of each node is enhanced by a coefficient modeling the amount of superimposed matrices. In the same manner, conflicting relations may exist between matrices or groups of matrices, on the condition that they share some misaligned superimposition (for instance in French, “placard” -- /plakaʁ/ meaning cupboard, and “carbone” -- /kaʁbɔn/ meaning carbon), while separate groups of matrices and isolated matrices would not interact. Therefore, in LEXSS, the lexicon is not an amorphous set of isolated units but a complex organization in which more elaborated structures and interactions occur between words than it was hypothesized in previous models of word recognition. The structure and functioning of a matrix is now going to be described.

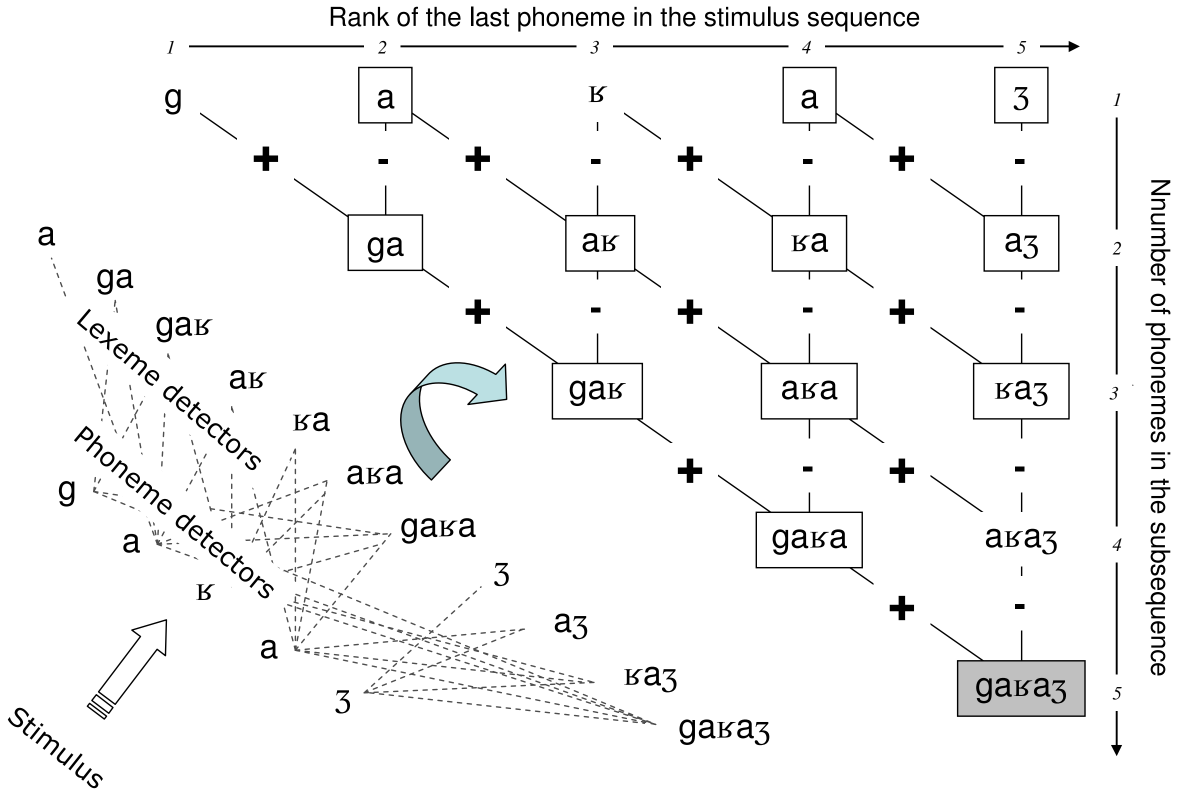
Structure of a matrix. Each matrix is a triangular matrix of nodes and links receiving and integrating inputs through its entire surface, and producing an output at its summit or last node. Each node is a processor receiving inputs from three sources and integrating this information with a set of functions. It generates two outputs sent to the two nodes to which it is directionally connected. Two factors organize a matrix. The first factor is the number of phonemes composing a sequence of $n-x$ phonemes contained in the word to which corresponds the matrix; n is the amount of phonemes composing this word, and $1<x<n$. The second factor is the rank, in the

sequence of phonemes composing the word, of the last phoneme from a given sequence excerpt. Combining these two factors defines the node's position in a matrix. For instance, the matrix for the word "love" has 6 nodes, [l], [ɔ], [v], [lɔ], [ɔv] and [lɔv]. These 6 nodes are respectively at positions [1:1], [1:2], [1:3], [2:2], [2:3] and [3:3] in the "matrix of love". The node [2:2] is the node for the two phonemes sequence [lɔ], which last phoneme corresponds to the second phoneme of the word "love". The node [2:3] corresponds to the 2 phonemes sequence [ɔv]. Its last phoneme is the third phoneme of the word "love". The node [3:3] corresponds to the word "love".

Lexeme detectors, located at the submatrix level, receive bottom-up activation from a sublexical layer of phoneme detectors. Lexemes are activated in proportion to this bottom-up flux, i.e. depending on their composition in terms of sublexical components. Therefore, for one stimulus word, a set of lexemes is activated simultaneously. Their activation propagates to the matrix level without lateral inhibition between them. Each lexeme is unidirectionally connected with the nodes of matrices including them. Note that one node of a matrix can be empty if no lexeme corresponds to a sublexical sequence (for instance, the node [2:3] in the matrix for the word "love" will be empty). One lexeme can be connected to more than one matrix (for instance the lexeme [ga] and the matrices for the French words "gars" and "gare"). It can also be connected to more than one node in the same matrix (for instance the lexeme [aʁ] corresponding to the embedded French word "art" – meaning art, in the matrix for the French word "barbare" – meaning barbarian).

Relations between nodes in a matrix are unidirectional and local. Only nodes corresponding to a sequence of n-1 phonemes can facilitate or inhibit nodes corresponding to a sequence of n phonemes according to the organization described hereafter. Let's consider a sequence of j phonemes composing a word A, and called Sequence A. Let's consider two shorter sequences included in A, composing two words, B and C, respectively of j-1 phonemes, called Sequence B, and of j-2 phonemes, called Sequence C. If the rank r_i of the last phoneme in Sequence B, corresponding to the node $[n_{j-1}:r_i]$ in the matrix of Word A, equals the rank r_i of the last phoneme in Sequence C, corresponding to the node $[n_{j-2}:r_i]$ in the matrix of Word A, the two sequences B and C are misaligned and the relation between the two nodes $[n_{j-1}:r_i]$ and $[n_{j-2}:r_i]$ is inhibitory. If the last phoneme in sequence C equals to r_{i-1} (corresponding to the node $[n_{j-2}:r_{i-1}]$ in the matrix of Word A), the two sequences B and C are aligned and the relation between nodes $[n_{j-2}:r_{i-1}]$ and $[n_{j-1}:r_i]$ is facilitatory. For instance, the node [3:3] (/gaʁ/) in the matrix for the word "garage" presented in Figure 6 is directly influenced by two nodes to which it is connected: [2:2] (/ga/) and [2:3] (/aʁ/). The node [2:2] excites the node [3:3] because sequences /ga/ and /gaʁ/ are aligned, but the node [2:3] inhibits it because its corresponding sequence /aʁ/ is misaligned with the sequence /gaʁ/.

Figure 6. Matrix structure in LEXSS: Example with the matrix of the word "garage"



Note. Nodes that have a corresponding lexeme in the lexicon are marked as squares in the matrix. Empty nodes only show the corresponding phoneme sequence. Links between nodes are marked with the plus sign when facilitatory, and the minus sign when inhibitory.

The node [3:3] is not directly influenced by nodes [1:1], [1:2] and [1:3]. However, these three nodes can influence the node [3:3] indirectly through nodes [2:2] and [2:3] by increasing or lowering the activation level of these 2 nodes, provided that none of them is empty. By doing so, non-linearity is introduced in the process.

Finally, if a node is empty (no corresponding lexeme), no bottom-up activation is received from the lexical level, nor from the sublexical level. Activation and inhibition received from within the matrix is not integrated through computation for an empty node does not process information. It simply transfers it as it receives it from the previous node site to the next node site, in straight line. For instance, the empty node [4:5] corresponding to the phoneme sequence [aʁaʒ] in the matrix of the word “garage” receives inhibition from node [3:5] ([ʁaʒ]) and transmits it directly to node [5:5] ([gaʁaʒ]). It also receives facilitation from node [3:4] ([aʁa]), that it would transmit directly to node [5:6] if it existed. In case of empty nodes, some basic integration processes of information are still possible through strength variations in the links between node sites, which might modulate the force of the signal on its path. For instance, in the matrix for the 5-phonemes French word “chenal” (/ʃønal/ meaning channel, see Figure 7), the node [2:5] ([al]) is not empty but nodes [3:5] and [4:5] are empty. The node [5:5] ([ʃønal]) will receive inhibition from the node [2:5] weighted by the links [2:5]-[3:5], [3:5]-[4:5] and [4:5]-[5:5].

To summarize connectivity principles in LEXSS, regarding the first matrix level, each node $[n_j:r_i]$ in a matrix has 5 links, except the $[n_j:1]$ nodes corresponding to one-phoneme lexemes, which have 2 missing links (intralayer input links), empty nodes which have 1 missing link (interlayer input link), final nodes $[n:r_i]$, which have one missing link (intralayer output facilitatory link), and the final node of the matrix which has 2 missing links (intralayer output links). Three of these 5 links are input links. One of these three links is a bottom-up interlayer facilitatory link, through which the node receives information from the lexeme level. The two other links are 2 intralayer horizontal links, through which the node receives information from the two immediate neighbor node sites within the matrix, the link with the node $[n_{j-1}:r_{i-1}]$ being facilitatory (alignment), the link with the node $[n_{j-1}:r_j]$ being inhibitory (misalignment). Two of the 5 links are output links sending information to the two immediate neighbor next node sites.

The link towards node [n_{j+1}:r_j] is inhibitory, the link towards node [n_{j+1}:r_{i+1}] is facilitatory. Figure 6 shows this organization for the matrix of the French word “garage”.

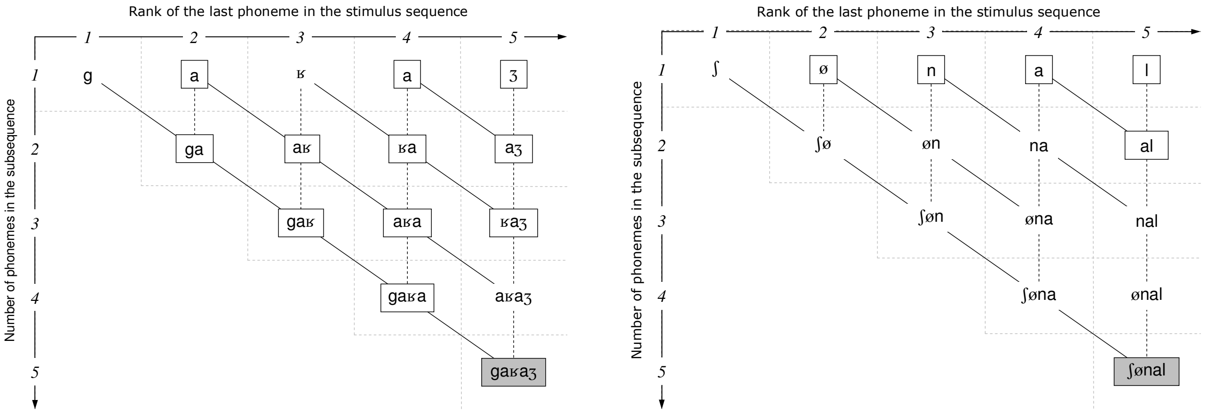
How a matrix works. Activation and inhibition propagate in the matrix following speech dynamics and the dynamics imposed by the matrix itself. Nodes are activated from the lexeme level in the following order: [1:1], [1:2] & [2:2], [1:3] & [2:3] & [3:3], etc. Nodes are activated from within the matrix in the following order: [2:2] from [1:1], [2:3] from [1:2] & [3:3] from [2:2], [2:4] from [1:3] & [3:4] from [2:3] & [2:3] & [4:4] from [3:3], etc. Nodes are inhibited from within the matrix in the following order: [2:2] from [1:2], [2:3] from [1:3] & [3:3] from [2:3], etc. Therefore, a matrix imposes its specific dynamics on percept building. If prosody and coarticulation were taken into account, propagation of activation and inhibition in the matrix could furthermore be modulated by the rhythm of speech and other contrastive phenomena, reinforcing the dynamic nature of word recognition. However, this would require that the sublexical layer feeding the matrix with bottom-up inputs is a sensory map and that the matrix is a more complex structure, in which nodes are compounds of sublexical and lexical detectors.

Depending on activation and inhibition patterns in a matrix, imposed by the very structure of a matrix, a node will have a different impact on a distant node. As a consequence, the last node of a matrix will be more or less activated depending on the lexical embedding structure encoded in the matrix. For instance, node [1:2] can influence indirectly node [3:3] if nodes [2:2] or [2:3] are not empty. However, this influence will not be the same depending on the path followed by information in the matrix. For instance, the path [1:2]-[2:2]-[3:3] will not result in the same activation score at node [3:3] compared to the path [1:2]-[2:3]-[3:3]. Let’s suppose, that a node receives activation equal to the number of phonemes composing the corresponding word, and integrates activation and inhibition through simple additive processes, the first path, following an aligned configuration, would give an activation level of 4 (details: (-1) + 2 + 3), while the second path, following a misaligned configuration, would give an activation level of 0 (details: -(1 + 2) + 3). This is the main reason why aligned embedded words will enhance recognition while misaligned embedded words will not contribute or will impair recognition. Indeed, if all initially embedded word may facilitate the carrier word, all non-initial embedded word will not impair the recognition of the carrier. In the case of the French word “garage”, for instance, the embedded word “ara” (macaw) does not inhibit “garage” (no direct link from /aʁa/ to /gaʁaʒ/), but “rage” (/ʁaʒ/ -- fury) does. The embedded word “ara” can only reduce the facilitation effect of the embedded word “gara” (parked) on the carrier word “garage” by reducing its activation level. Therefore, the embedded word “ara” indirectly affects the stimulus carrier word by reducing the benefit on recognition of one of the aligned embedded words, but does not hinder recognition itself. Another phenomenon may occur if a word containing 2 embedded words can be split into these two words, like “garage” (“gars” and “rage”). Indeed, the corresponding matrices for the two embedded words will react and may induce lexical segmentation in the perception. This issue finds appropriate solution if additional sources of information like semantics and prosody are integrated in the process of percept building, reinforcing one solution over another. Following this multiple constraint satisfaction process, if the word sequence “gars” + “rage” was not meaningless (and therefore will not exist in discourse), it would be produced as a different acoustic pattern than that of the unique word “garage”.

The structure and functioning of LEXSS has been partially translated in equations (Lachaud, 2005), which allowed computing activation scores corresponding to the “perceptual vividness” of words. A word with a high vividness score will be recognized faster and more easily than a word with a lower vividness score, simply because it has the highest perceptual pregnance, driving it to pop-up in the mind and passively hide lexical alternatives.

Testing LEXSS. Comparing two extreme cases of 5-phonemes words, one containing cascaded initial embeddings (the stimulus word starts with more than one aligned embedded word) like the French word "garage" (garage) with another containing no initial lexical embedding like the French word "chenal" (channel), LEXSS predicts that "garage" will be recognized faster than "chenal" because "garage" is perceptually more vivid due to cascaded initial lexical embeddings. Figure 7 shows the superimposing structure of these two words through their respective matrices.

Figure 7. Lexical matrices for the French words "garage" and "chenal".



LEXSS gives a vividness score of 6.8 for "garage" vs. 1.8 for "chenal". Reaction times measured from 71 French monolingual normal young adults participating in a "go, no-go" lexical decision task experiment measuring their reaction on word detection are congruent with the prediction of LEXSS. Means were respectively 783 ms and 895 ms, showing a 112 ms significant difference, F(1, 106) = 18.4, p < .0001.[2]

The predictive property on human behavior (71 subjects), of score differences due to the lexical superimposing structure of stimuli, was confirmed with a set of 80 disyllabic monomorphemic French words of 4 to 8 phonemes.[3] These words were selected for an experiment investigating specifically the effect of lexical embedding structure on spoken word recognition (Experiment 7, Lachaud, 2005), which manipulated two factors: first syllable's lexicality (word W vs. nonword nW) and second syllable's lexicality (W vs. nW). The two experimental factors were crossed, resulting in four conditions (W1W2, W1nW2, nW1W2, nW1nW2), twenty words in each. Vividness scores given by LEXSS (see Lachaud, 2005) was on average almost double[4] in the case of words starting with a lexical syllable compared to words starting with a non-lexical syllable, $\chi^2(1, N = 80) = 19$; $p < .0001$.[5] The difference was not significant depending on second syllable's lexicality, and there was no interaction between the lexicality of first and second syllables. This pattern of effects follows the pattern of effects found in the reaction times measured on these 80 words.[6] Acoustic parameters like word duration,[7]

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[2] Outlier reaction times were filtered out with a ±3 standard deviation rule applied to each subject and each item. Missing values (33 out of 140 measurements) were not replaced for the analysis. An ANOVA by subject was run, the experimental factor being conflated with the items level.

[3] Average length in phonemes, per condition: nW1nW2: 5.95; W1nW2: 5.55; nW1W2: 5.7; W1W2: 5.5.

[4] Average scores per condition (no unit): nW1nW2: 2.7; W1nW2: 6.3; nW1W2: 2.2; W1W2: 5.2.

[5] The statistic test is a large sampled Chi square test comparing the distribution of LEXSS scores predicted by a model integrating the experimental factor being tested as a predictor, to the distribution predicted by a model without this specific experimental factor.

[6] Average reaction times per condition (ms): nW1nW2: 766; W1nW2: 712; nW1W2: 782; W1W2: 704.

[7] nW1nW2: 705 ms; W1nW2: 700 ms; nW1W2: 680 ms; W1W2: 692 ms.

position of the recognition point and uniqueness point[8] were controlled experimentally or statistically and could not be the cause of these behavioral differences, as well as lexical frequency, Age of acquisition and Familiarity. Vividness scores given by LEXSS for each of these 80 words were tested as linear predictors of reaction times.[9] LEXSS scores were found to be significantly related to the reaction times, $\chi^2(1, N = 5296) = 5.6$, $p < .02$, confirming that the model has some psychological reality.

LEXSS is of course a first attempt to provide an explanation to the phenomenon of facilitation produced by lexical embeddings on the recognition of their carriers. At this stage of development, it cannot be considered as a model fully able to predict various aspects of spoken word recognition. Although preliminary tests presented in (Lachaud, 2005) have shown some inconsistencies, overall results reveal a good adequacy between the predictions of LEXSS and human behavior. More development and testing are therefore required, particularly concerning the mathematical aspects. Consequently, LEXSS appears as a promising start for the development of new research hypotheses.

Conclusion

The theoretical work presented in this article, by first showing that initial lexical embeddings could never facilitate the recognition of their carrier word in TRACE-like localist

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[8] Position of the recognition point and was measured in ms in the acoustic signal. The recognition point was defined as the minimal amount of signal below which it is impossible to have recognized the word. This parameter was controlled statistically by including it in the model as fixed factor, in order to part its variance from the variance of the experimental factors. Chi2 (1, N = 5296) = 5.7; p < .02. The position of the Uniqueness Point was measured in ms in the acoustic signal. It was defined as the moment where it becomes possible to identify the beginning of the phoneme corresponding to the uniqueness point by taking into account coarticulation. Chi2 (1, N = 5296) = 2.6; p < .11. All measurements were done by 3 phoneticians and crossed-validated between them.

[9] Reaction times were obtained from the same experiment than those used previously for the case study comparing two words. They were filtered using the same procedure and analyzed with a multilevel model crossing items and subjects as random variables, and LEXSS scores as fixed predictor.

models via resonance and activation transfer, has answered colleagues' speculations on the mechanisms behind some behavioral observations in humans. Simulations with jTRACE exploring whether top-down feedback could facilitate carrier words' recognition in case of initial lexical embeddings proved that the resonance mechanism fails to model human perception adequately. Further simulations with jTRACE, exploring if a priming mechanism based on the activation transfer from the lexeme of the embedded word to the lexeme of the carrier word, as suggested by Luce and Lyons (1999), also failed in this attempt.

Second, the theoretical work presented in this article, by showing that it was possible to explain facilitation caused by initial lexical embeddings with alternative models involving supra-lexical structures in the mental lexicon, has opened new fields of research in word recognition. Through two models, LML and LEXSS, it was possible, not only to come with explanative mechanisms, but to provide a set of predictions, regarding for instance the existence of metastructures in the mental lexicon.

Finally, simulations with LEXSS and confrontation of its predictions with behavioral measurements from humans have proved that this type of model has some psychological validity. Activation scores produced by LEXSS for a set of 80 French words, for which recognition times were also measured in a French population, were significantly predicting reaction times.

In conclusion, this theoretical work opens a new track of research, from models development to the testing of their predictions, by opening the box beyond lateral inhibition.

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