

Attention and Performance XVI: Information Integration in Perception and Communication

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16 Integration of Multiple Sources of Information in Language Processing

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ABSTRACT

It is now indisputable that language processing is influenced by multiple sources of information. Understanding spoken language is constrained by a variety of sensory cues, as well as lexical, semantic, syntactic, and pragmatic constraints. Research questions include the nature of the sources of information, how each source is evaluated and represented, how the multiple sources are treated, whether or not the sources are integrated, the nature of the integration process, how decisions are made, and the time course of processing. The fuzzy logical model of perception (FLMP) is shown to give a better description of performance than a formalized horse race (RACE) model and a postperceptual guessing (PPG) model; research findings also falsify the predictions of the interactive activation model. Research in a variety of domains and tasks supports the conclusions that (1) perceivers have continuous rather than categorical information from each source; (2) each source is evaluated with respect to the degree of support for each alternative; (3) each source is treated independently of other sources; (4) the sources are integrated to give an overall degree of support for each alternative; (5) decisions are made with respect to the relative goodness of match; (6) evaluation, integration, and decision are necessarily successive but overlapping stages of processing; and (7) cross talk among the sources of information is minimal. The FLMP, which embodies these properties, gives the best extant account of language processing.

It is worth reflecting on the theme of Attention and Performance XVI, integration, which is more or less the antithesis of attention. Attention has traditionally been viewed as a screening device to protect information-challenged actors from environmental overload: we attend to some information at the expense of processing other information or we even actively filter out some input so that other input can be more accurately processed. Integration provides an alternative perspective because it stresses the combination of the many inputs or sources of information available to the perceiver. Although the attention metaphor has dominated much of the research since the birth of this organization, today it is more commonplace to give less emphasis to attentive processes and to accept an organism's ability to combine several seemingly disparate pieces of information. The study of how multiple sources of information are put together to guide performance has been the theme of our work for almost two decades (Massaro and Cohen 1976; Oden and Massaro 1978; see also Oden and Anderson 1974; Anderson 1981). The present chapter continues this theme in the domain of perceiving

and understanding language; it begins with a brief description of our general perspective and paradigm of inquiry.

16.1 INFORMATION PROCESSING ANALYSIS OF LANGUAGE

Stages of information processing and hierarchical processing have been central to our approach to the study of psychological phenomena (Massaro 1975a,b, 1987). It is assumed, for example, that there are at least four stages of processing a language pattern: sensory transduction, sensory cues, perceived attributes, and conceptual understanding. Human sensory systems transduce linguistic input and make available a configuration of sensory cues. Perceived attributes correspond to the outcome of processing these cues. As in other domains of pattern recognition, there is a many-to-one relationship between sensory cues and perceived attributes (Bennett, Hoffman, and Prakash 1989; Massaro and Cowan 1993). For example, information about the syntactic structure of a spoken utterance is conveyed not only by pitch but also by duration and the actual words being used. In turn, there is a one-to-many relationship between a sensory cue and the resulting perceived attributes. The pitch of the speaker's voice provides segmental information and information about the syntactic structure of the utterance, as well as the age, gender, and affective state of the speaker (Murray and Arnott 1993). In an analogous fashion, perceived attributes and conceptual understanding are not necessarily uniquely associated. Identical percepts can take on different meanings, and the same meaning can be created by entirely different percepts. The plethora of homophones in English, such as *see* and *sea*, produce different meanings with the same phonological form, while the different phonological forms *sea* and *ocean* can produce more or less the same meaning.

Language processing can be viewed as highly analogous to visual perception and recognition. Our current understanding of perception might be summarized as (1) perception is a process of inference; (2) perceptual inference is not deductively valid; and (3) perceptual inferences are biased (Bennett, Hoffman, and Prakash 1989). Assumptions 1 and 2 go back to at least Helmholtz and are easily illustrated. Given the statement,

Biting alligators can be dangerous,

the perceiver might infer that alligators that bite are a threat when the speaker might actually be referring to the new sport of people biting alligators. Assumption 3 simply means that the perceptual system is biased toward some interpretations in preference to others. A homograph ("kind") appears to be initially interpreted in terms of its most frequent meaning (see MacDonald, chap. 17, this volume). These three assumptions confront the inverse mapping problem. In language processing, we seek the intended meaning, given the multiple linguistic and situational cues.

We operate on the assumption that general principles of pattern recognition provide a productive approach to the study of language processing.

What message is intended, given the multidimensional language input? Thus language processing is also envisioned as a biased inferential process. Given some linguistic event, the best interpretation is usually supported by several cues in addition to being biased. For example, if the many different cues are made ambiguous to create a phonological form between a word and a nonword, we will tend to perceive it as the word (Ganong 1980). Given the assumption that language processing is best conceptualized as pattern recognition, it is worthwhile to consider the most appropriate definition of language recognition.

16.2 LANGUAGE RECOGNITION

What does it mean to recognize a linguistic pattern such as a word? I assume that word recognition is a part of the broader concept of language comprehension. Consider the popular riddle "How many animals did Moses bring on the ark?" Most people find this a perfectly acceptable question and give some quantitative reply. They do not notice or understand at the time of the question that the lead character in the riddle's version of this biblical event is not Noah but Moses (Erickson and Mattson 1981; Reder and Kusbit, 1991). Aspects of the appropriate biblical event are quickly called to mind even if the main player or other details are incorrect. Comprehension appears to be a matter of degree (graded); there are different degrees of understanding of our example riddle. For example, one person answered 40 animals, 20 of each sex, confusing the 40 days of rain with the number of animals. In addition, understanding is dynamic in that it fluctuates across time—for example, the change in understanding when we become aware of the misplaced biblical character. (MacDonald, chap. 17, this volume, presents analogous arguments for graded and dynamic activation of meaning. Similarly, sentence interpretation is more ambiguous than the discrete interpretations usually given by psycholinguists; see Altmann, chap. 19, this volume.)

At issue is whether word recognition is any different from comprehension in terms of its graded quality. Of course, my view is that the outcome of word recognition is graded in the same way that comprehension is graded. Most investigators, on the other hand, have assumed that the outcome of word recognition either occurs or does not. This all-or-none property is also reflected in our models of word recognition, beginning with Morton's (1969) seminal logogen model with a threshold for each word and Forster's (1985) search model of lexical access to the more recent cohort (Marslen-Wilson 1984) and activation-verification models (Paap et al. 1982). Much of contemporary research also reflects the implicit assumption of discrete word recognition. There is a good deal of debate about the number of activated meanings given presentation of a polysemous word, but the all-or-none property of a given meaning is not usually questioned.

However, there are hints of evidence for graded word recognition. Abrams and Balota (1991), for example, found that the strength of a key press was

related to the frequency of the test word. Connine, Blasko, and Wong (1994) demonstrated that word recognition might be graded. An ambiguous prime was made by modifying the initial phoneme before /ent/ to be ambiguous between /d/ and /t/; in this case, the prime was an ambiguous word between *dent* and *tent*. Ambiguous primes of this type facilitated lexical decisions for both meanings of the prime, indicating perhaps multiple and graded activation. Thus we should keep in mind the caveat that word recognition is unlikely to be all-or-none. The next section reviews two opposing views of language processing.

16.3 AUTONOMOUS VERSUS INTEGRATION MODELS

Like many other investigators, my research has addressed a distinction between autonomous and integration models of language processing (Massaro 1987, 1989a). Although this distinction can be formulated around a variety of characteristics, a major difference has to do with how several linguistic variables influence performance. Early, strictly modular views proposed that a linguistic process such as phoneme recognition is triggered by a primary source of information (e.g., auditory speech in terms of phonetic features) and is not perturbed by other sources such as lexical, syntactic, and semantic context (Fodor 1983). Integration models, on the other hand, proposed that these multiple sources of information are combined during linguistic processing (Massaro 1975b; Oden 1977). Thus much of the debate has centered on how bottom-up and top-down sources are processed. Bottom-up sources correspond to those sources that have a direct mapping between the sensory input and the representational unit in question; top-down sources come from contextual constraints that are *not* directly mapped onto the unit in question. As an example, a bottom-up source would be the stimulus presentation of a test word after the presentation of a top-down source, a sentence context. A critical question for both integration and autonomous (modularity) models is how bottom-up and top-down sources of information work together to achieve word recognition. For example, an important question is how early can contextual information be integrated with acoustic-phonetic information. A large body of research shows that several bottom-up sources are evaluated in parallel and integrated to achieve recognition (Massaro 1987, 1994). An important question is whether top-down and bottom-up sources are processed in the same manner.

Previous theories have not always been clear about how bottom-up and top-down sources are processed. Marslen-Wilson (1987) distinguishes among access, selection, and integration. *Access*, or activation, corresponds to the mapping of the speech input onto lexical representations; *selection* involves selecting the word form that best matches the input and context; and *integration* means associating the syntactic and semantic information at the word level onto higher levels of processing. For Marslen-Wilson, a bottom-up

source would necessarily influence access, and the top-down source would influence only selection. Early selection “means that the acoustic-phonetic and the contextual constraint on the identity of a word can be integrated together at a point in time when each source of constraint is inadequate, by itself, to uniquely specify the correct candidate” (Marslen-Wilson 1987, 77). Needless to say, the selection process has to be specified exactly to describe how the bottom-up and top-down sources work together to achieve performance of this kind.

Tyler (1990) observes that top-down context cannot affect activation or selection if autonomous models are correct but must somehow play a role later in processing. It has been shown that subjects are more likely to identify an ambiguous phoneme as one that makes a word (Ganong 1980). Given Tyler’s reasoning, lexical context must somehow influence performance after activation and selection of the phoneme have occurred in an autonomous fashion. This reasoning is not necessarily true, however; in the RACE model (Cutler et al. 1987), for example, subjects can respond at the word level even if activation and selection at the phoneme level are not yet finished. That is, the response can be based on only the word information without any additional influence from the test segment in the test word.

Thompson and Altmann (1990) make a distinction between selection and instruction in the framework of a speech recognition system. A word lattice is created based on bottom-up processing, and selection only allows filtering of candidates after they have entered the word lattice. Syntactic processing does not influence which words are placed in the word lattice. Instruction, on the other hand, allows syntactic processing to influence which words are entered into the word lattice. It is assumed, for example, that analysis by synthesis of candidates occurs on the basis of grammatical information. In the instruction case, processing at the grammatical level penetrates the processing at the word level; within this framework, the issue of autonomous versus integrative processes might boil down to whether instruction occurs.

I take the critical characteristic of autonomous models to be the language user’s *inability* to integrate bottom-up and top-down information. Integration will be defined within a formal model of language processing. To attempt to add some order to the plethora of possibilities, we consider integration of top-down and bottom-up information as the touchstone distinguishing between autonomous and nonautonomous models. In my view, the autonomous model must necessarily predict no perceptual integration of top-down with bottom-up information.

As perhaps apparent in the debate between autonomous and integration viewpoints, specific predictions and tests are not easy. It is proposed that our science will make progress only with the formalization and test of specific models of language processing. In this chapter I formalize and test two prototypical autonomous models as well as an integration model. The integration model is the fuzzy logical model of perception (FLMP), which has

been tested extensively in a broad number of domains. The autonomous models are a horse race model (RACE), and a postperceptual guessing (PPG) model, which are new formalizations of existing autonomous views. Thus I use a falsification and strong-inference strategy of inquiry (Massaro 1987, 1989a; Platt 1964; Popper 1959). Results are informative only to the degree that they distinguish among alternative theories. The experimental task, data analysis, and model testing are devised specifically to attempt to reject some theoretical alternatives. Our first goal, of course, is to distinguish between autonomous and integration models. The FLMP has been very successful, and I begin with the description of this model.

16.4 FUZZY LOGICAL MODEL OF PERCEPTION (FLMP)

The results from a wide variety of experiments have been described within the framework of the FLMP. Within the framework shown in figure 16.1, language processing is robust because there are usually multiple sources of information that the perceiver evaluates and integrates to achieve perceptual recognition. According to the FLMP, patterns are recognized in accordance with a general algorithm, regardless of the modality or particular nature of the patterns. The assumptions central to the model are (1) each source of information is evaluated to give the degree to which that source supports the relevant alternatives; (2) the sources of information are evaluated independently of one another; (3) the sources are integrated to provide an overall degree of support for each alternative; and (4) perceptual identification follows the relative degree of support among the alternatives.

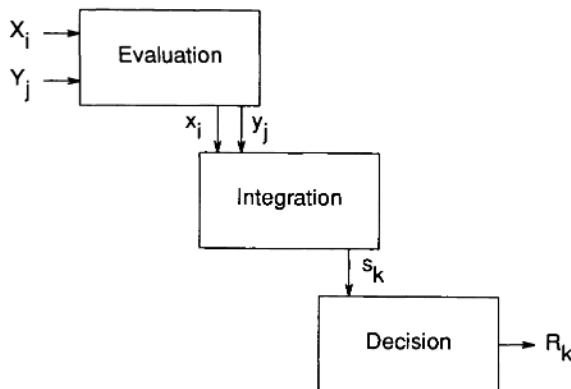


Figure 16.1 Schematic representation of three stages involved in perceptual recognition. Three stages are shown to proceed left to right in time to illustrate their necessarily successive but overlapping processing. Sources of information are represented by uppercase letters (indicated by uppercase letters X_i and Y_j). Evaluation process transforms these sources of information into psychological values (indicated by lowercase letters x_i and y_j). These sources are then integrated to give overall degree of support for given alternative s_k . Decision operation maps this value into some response, R_k , such as discrete decision or rating.

16.5 FLMP ACCOUNT OF LEXICAL CONTEXT

The experimental task we use was first tested by Ganong (1980), who established that lexical identity could influence phonetic judgments. A continuum of test items was made by varying the voice onset time (VOT) of the initial stop consonant of CVC syllables; the VC was also varied. For example, subjects identified the initial consonant as /d/ or /t/ in the context /æʃ/ (where /d/ makes a word *dash* and /t/ does not), or in the context /æsk/ (where /t/ makes a word *task* and /d/ does not). Both the segmental information of the initial phoneme and the lexical context influenced performance. The top panel of figure 16.2 shows that the percentage of voiced judgments decreased as the initial segment was changed from /t/ to /d/. A lexical context effect was also observed because there were more voiced judgments /d/ in the context /æʃ/ than in the context /æsk/. The bottom panel of figure 16.2 shows similar results for the contexts supporting the words *dirt* and *turf*. Significantly, this lexical effect was largest at the most ambiguous intermediate levels of VOT, which is consistent with the general principle that the least

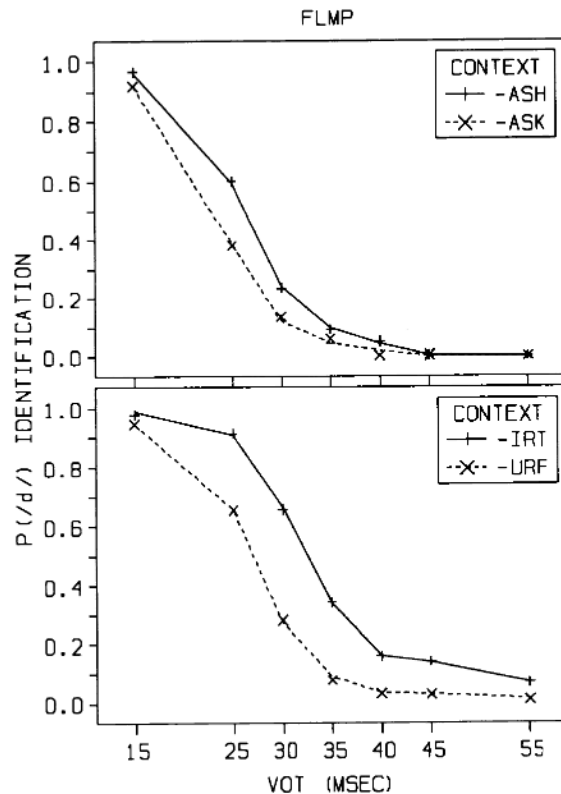


Figure 16.2 Observed (points) and predicted (lines) proportion of /d/ identification for *-ash* and *-ask* contexts (top panel) and *-irt* and *-urf* contexts (bottom panel) as function of VOT. (Observed data from Ganong 1980). Predictions of FLMP.

ambiguous source has the most influence on perception. Ganong's original results have been replicated and extended by several investigators (Connine and Clifton 1987; McQueen 1991; Pitt and Samuel 1993).

According to the FLMP, there are two sources of information in the Ganong (1980) task: the bottom-up information from the initial speech segment and the following top-down context. It is assumed that both of the sources are evaluated and integrated to achieve perceptual identification. The evaluation process provides continuous information indicating the degree to which each source of information supports each alternative. This continuous information is represented in terms of fuzzy truth values that lie between 0 (no support) and 1 (complete support); with two response alternatives, as in the Ganong (1980) task, .5 is completely ambiguous support. Furthermore, with just two response alternatives, the support of a source of information for one alternative is 1 minus its support for the other alternative. At the integration operation, the total support for a given alternative is given by the multiplicative combination of the two separate sources of support. Finally, the decision operation follows a relative goodness rule (RGR): a response is based on the total support for that alternative relative to the total support for both alternatives.

Assume that s_i is the information supporting the voiced alternative given by the initial segment and that c_j is the support for the voiced alternative given by the following context. The subscripts i and j index the different levels of the segment and the context. In this case, the total support S for the voiced alternative, given segmental information S_i and lexical context C_j , would be

$$S(\text{voiced}|S_i \text{ and } C_j) = s_i \times c_j. \quad (16.1)$$

The total support for the voiceless alternative would be

$$S(\text{voiceless}|S_i \text{ and } C_j) = (1 - s_i) \times (1 - c_j). \quad (16.2)$$

Given the RGR at the decision stage, the predicted probability of a voiced response, $P(\text{voiced}|S_i \text{ and } C_j)$, is equal to

$$P(\text{voiced}|S_i \text{ and } C_j) = \frac{s_i \times c_j}{[s_i \times c_j] + [(1 - s_i) \times (1 - c_j)]}. \quad (16.3)$$

This model was applied to two sets of results from Ganong's original study (Massaro and Oden 1980). With 7 levels of bottom-up information and 2 different contexts, 7 values of s_i and 2 values of c_j must be estimated to predict the results. Thus 9 free parameters are used to predict the 14 independent data points in each of two different experiments; these parameters are estimated by a search routine that minimized the squared differences between the observed and predicted values (Chandler 1969). As can be seen from the close match between the observed points and predicted lines in figure 16.2, the FLMP gives a good description of the results. Thus the model captures the observed interaction between segmental information and lexical

context: the effect of context is greater to the extent that the segmental information is ambiguous. This yields two curves in the shape of an American football, which is a trademark of the FLMP.

16.6 INDIVIDUAL VERSUS GROUP RESULTS

Until recently, the Ganong (1980) task has not been carried out to allow individual subject analyses; indeed, most, if not all, psycholinguistic studies of top-down and bottom-up sources of information only present results pooled across subjects. In general, we have found that average results are fairly representative of the subjects that make up the average, although there is reason to be cautious with average results (Massaro and Cohen 1993). For example, average results tend to favor linear over nonlinear models. In any event, a high priority in psycholinguistic research should be to test extant models against results of individual subjects. The primary modifications of the typical research strategy would require a much larger number of observations for each subject and the testing of formal models against the individual results. Although the interaction of bottom-up and top-down sources of information has been of central interest in the last decades of research on language processing, the number of studies with individual results can be counted on a single hand. We hope that future research will test individuals more thoroughly so that competing models can be developed and tested against individual performance.

Pitt (1995) carried out an extensive study of lexical context effects in the Ganong task. Contrary to tradition, a large number of observations were recorded for each subject providing an opportunity to test formal models against individual performance. In Pitt's task, the initial consonant was varied along six steps between /g/ and /k/ and the following context was either /ift/ or /ls/. In this case, the context /ift/ would bias subjects to perceive /g/ as in *gift* and the context /ls/ would bias subjects to perceive /k/ as in *kiss*. Massaro and Oden (1995) tested the FLMP against the identification results of the 12 individual subjects in Pitt's experiment 3a for which a very large number of observations (104) were obtained for each data point for each subject. The points in figure 16.3 give the observed results for each of the 12 subjects in the task; for most of the subjects, the individual results tend to resemble the average results reported by Pitt and earlier investigators. Ten of the 12 subjects were influenced by lexical context in the appropriate direction. Subject 1 gave an inverse context effect, and subject 7 was not influenced by context.

In producing predictions for the FLMP, it is necessary to estimate parameter values for the 6 levels of bottom-up information and the 2 lexical contexts. Thus 8 free parameters are used to predict the 12 independent probabilities of a voicing judgment: 6 values of s_i and 2 values of c_j . The lines in figure 16.3 give the predictions of the FLMP; the good description of the results is apparent in the figure and in the small root mean squared deviation

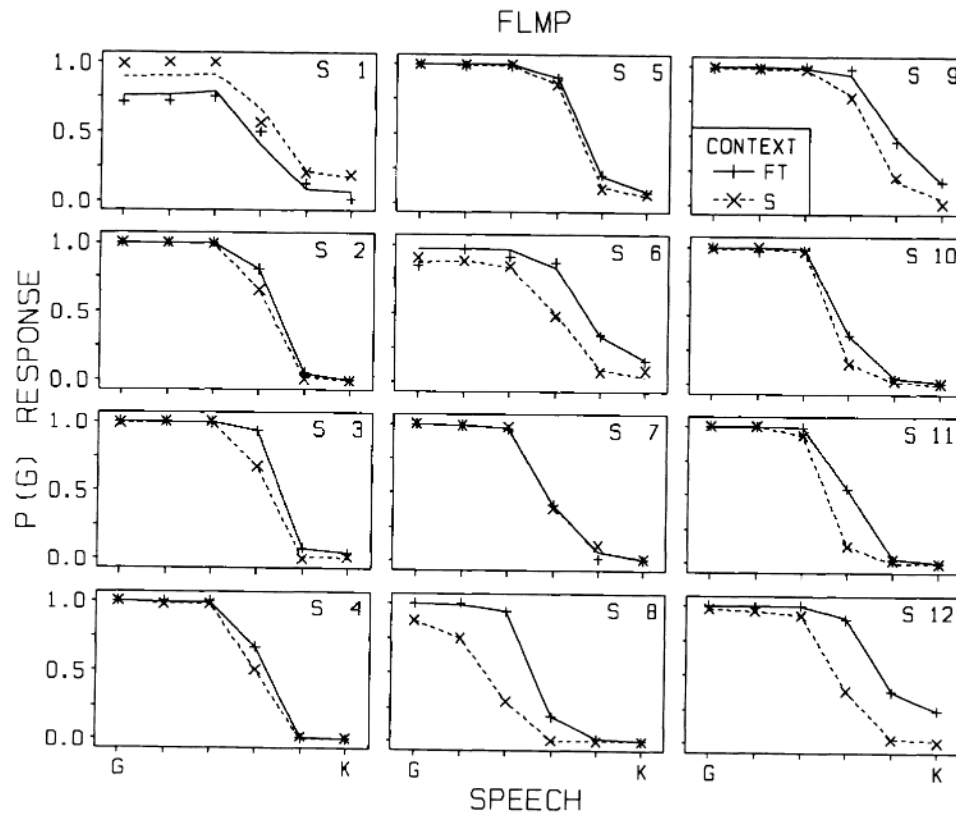


Figure 16.3 Observed (points) and predicted (lines) proportion of /g/ identifications for /ft/ and /ls/ contexts as function of speech information of initial consonant. Results from Pitt's (1995) experiment 3a. Predictions are for FLMP.

(RMSD) between predicted and observed values. The RMSD is .017 on the average across all 12 independent fits.

Subject 1 showed a context effect in the opposite direction to the other subjects (and to reasonable expectation). The FLMP gave a very poor description of this subject's results, yielding an RMSD of .066. This poor fit is impressive because it demonstrates that the FLMP is not so powerful that it can fit any possible result. The repeated success of the model appears to have led some researchers to suspect that it uses excessive free parameters or has some other "unfair" advantage that somehow makes it effectively unfalsifiable. Such suspicions were argued to be wholly unfounded (see Massaro and Cohen 1993), and this result supports this argument.

Although the FLMP provides a good description of the results, it is worthwhile to have a benchmark indicating how good is good. Even if a model is perfectly correct, we cannot expect it to fit observed results exactly. Reasonably accurate models must be stochastic or have built-in variability, as do observed results. The current FLMP is deterministic (has no variability) at the feature evaluation and integration processes, and becomes stochastic only at

the decision process. The variability at the decision process is due to the RGR, in which the probability of a response alternative is equal to the merit of a particular alternative, relative to the sum of the merits of all relevant alternatives. If we know the observed probabilities and the number of observations, a benchmark RMSD can be determined and compared to the observed RMSD (see Massaro and Cohen 1993). The average of these 12 benchmarks for the results in figure 16.3 was .024, not significantly different from the observed RMSDs that averaged .017. Thus we can conclude that the FLMP described the results as accurately as could be expected from any correct model; for Pitt's results, we cannot expect an autonomous model to do any better than the FLMP. The question must be reformulated to ask whether there is an autonomous processing model that can do as well. We now examine two such autonomous viewpoints.

16.7 POSTPERCEPTUAL GUESSING (PPG) MODEL

One autonomous explanation of context effects in speech perception is that they occur only when the bottom-up information is ambiguous. An important property of this model is discreteness: recognition either occurs via the bottom-up information or it does not. When it does not, top-down information is used to make a judgment. This model appears to represent the more general view that context effects are postperceptual. Some investigators have argued that certain context effects are indeed postperceptual. For example, Samuel (1981) claims that bias effects, but not sensitivity effects, in the phonemic restoration task are postperceptual. Connine (1990) claimed that RTs of perceptual judgments can distinguish between perceptual and postperceptual effects; her task evaluated sentence context and segment processing in an extension of the Ganong (1980) task. The speech continuum consisted of syllables varying between *dent* and *tent*. The sentence context could be biased toward either of these two alternatives. The identification judgments were analogous to those found in the lexical studies; there was a strong bottom-up influence and a small effect of context for the ambiguous tokens between the two alternatives. Based on an analysis of the RTs, Connine argued that the influence of sentence context was necessarily postperceptual. If this is the case, then her results do not challenge autonomous models. More generally, advocates of modularity are quick to interpret positive findings of top-down context on putative bottom-up processing as postperceptual. Without formal models, deciding between perceptual and post-perceptual effects is not at all easy.

Instantiation of the PPG model for Ganong (1980) task assumes that context has a possible influence *only* when the sensory input from the initial phoneme is not identified. There are two types of trials: those when the voicing of the initial phoneme is identified and those when it is not. When voicing identification of the segmental source is successful, the perceiver responds with the appropriate alternative. When no identification is made,

the perceiver uses the context to identify the initial segment. It is assumed that the probability of a voiced judgment, given a lexical context C_j , is g_j , labeled as such to emphasize its postperceptual guessing origin. The predicted probability of a voiced response is thus equal to

$$P(\text{voiced}|S_i \text{ and } C_j) = v_i + (1 - v_i - vs_i)c_j. \quad (16.4)$$

where v_i is the probability of identifying the segmental source as a voiced response, and vs_i is the probability of identifying the segmental source as voiceless. The term $(1 - v_i - vs_i)$ is the probability of not identifying the voicing of the segmental source, and g_j is the bias to respond with the voiced alternative when the voicing of the segmental source is not identified. Equation 16.4 represents the postperceptual theory that the voicing of the initial segmental source is either identified or else lexical context is used. The lexical context has an influence only when the initial segment is not identified. The model requires v_i , vs_i , and c_j parameters.

In Pitt's (1995) study with 6 levels of bottom-up segmental information, 6 free parameters are necessary for identifying the initial segment as the voiced alternative and 6 as the voiceless one; the bias g_j must be estimated for each of the two lexical contexts. Unfortunately, a total of $6 + 6 + 2 = 14$ free parameters are necessary to predict just 12 independent data points. Thus it appears that the PPG model cannot be fairly tested against the results because the number of free parameters exceeds the number of independent data points.

Another strategy is to impose some constraints on the model to reduce the number of free parameters. One possibility is to assume that the two endpoint stimuli on each of the two ends of the segmental continuum are never identified as the inappropriate alternative. That is, the two stimuli at the voiced end are never identified as voiceless, and the two stimuli at the voiceless end are never identified as voiced. This constraint reduces the number of free parameters to 10, which is still 2 more than the FLMP; it seems reasonable because it still allows for the possibility that the voicing of the 2 middle levels of the segment is not identified. The constrained model does a poor job of describing the results, with an RMSD of .068, significantly worse than the FLMP. Another constraint is to assume that the perceiver *always* responds in accordance with the lexical context when the segmental information is not identified. This model, with 12 parameters, does equally poorly with an RMSD of .067. Given that potential advocates of the PPG model might reject these constrained models as being unrealistic, we are fortunate to have a set of results in which the number of free parameters for the PPG model does not exceed the number of data points.

16.8 PHONOLOGICAL CONTEXT

The role of phonological context has been studied in the same manner as lexical context. Massaro and Cohen (1983) studied the contribution of pho-

nological constraints in a speech identification task. Subjects were presented with CCV syllables, with the first consonant being /p/, /v/, /t/, or /s/, the second consonant being one of seven glides equally spaced on a continuum between /l/ and /r/, and with the vowel being /i/. The glide was changed from /l/ to /r/ by changing its initial third formant frequency from high to low. The rationale was that perceivers have two sources of information: the segmental information about the glide and the phonological context. In English the segment /r/ is admissible when it follows initial /p/ and /t/, but not initial /s/ and /v/. Similarly, the segment /l/ is admissible when it follows initial /p/ and /s/, but not initial /t/ and /v/. Seven subjects were tested on the 7 times 4 = 28 experimental conditions, with 40 observations per condition. The percentages of /r/ identifications for three of the subjects are shown in figure 16.4, along with the predictions of the FLMP. Both the bottom-up glide information and the top-down phonological context influenced performance; in addition, the contribution of one source was larger to the extent the other source was ambiguous. The FLMP provided a good description of these results of the individual subjects, with an average RMSD of .055 (see Massaro and Cohen 1991).

Instantiation of the PPC model for this task assumes that context has a possible influence *only* when the bottom-up input from the glide is not

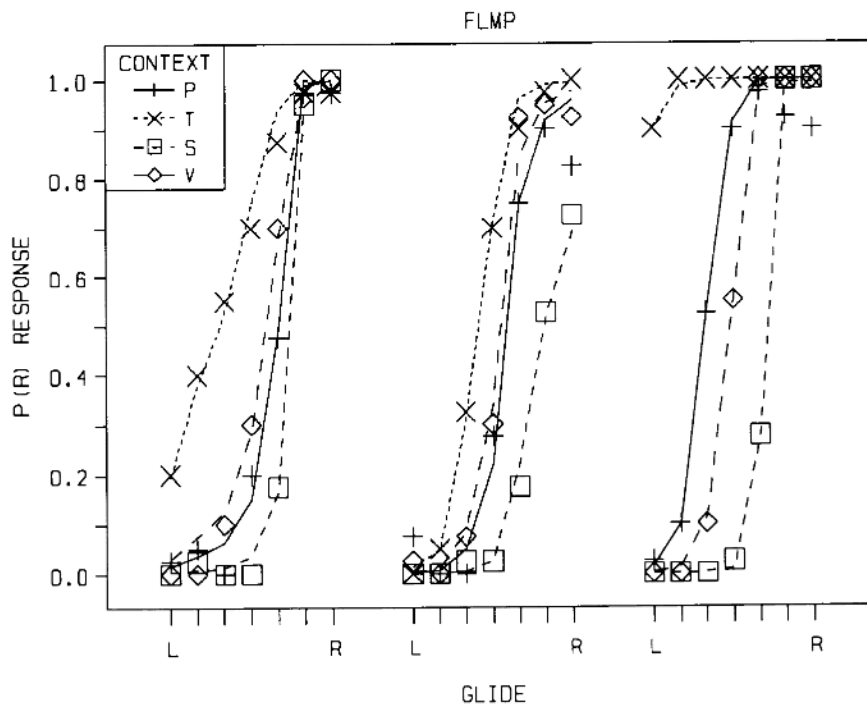


Figure 16.4 Observed (points) and predicted (lines) probability of *r* response for three typical subjects as function of glide F_3 onset level and context (after Massaro and Cohen 1983, experiment 2). Predictions are for FLMP.

identified. When identification of the bottom-up input is successful, the perceiver responds with the appropriate alternative. Where no identification is made, the perceiver uses the top-down phonological context to identify the initial segment. It is assumed that the probability of a /r/ judgment, given a phonological context C_j , is g_j . The predicted probability of a /r/ response is thus equal to

$$P(r|S_i \text{ and } C_j) = r_i + (1 - r_i - l_i)g_j, \quad (16.5)$$

where r_i is the probability of identifying the bottom-up source as /r/; l_i is the probability of identifying the bottom-up source as /l/; and g_j is the bias to respond with /r/ when the the bottom-up source is not identified. The phonological context has an influence only when the bottom-up source is not identified. The model requires 7 r_i , 7 l_i , and 4 g_j parameters. These 18 free parameters are fewer than the 28 independent data points, but still 7 more than the 11 free parameters required by the FLMP. The fit of the PPG model is shown in figure 16.5. The fit to the individual subjects gave an average RMSD of .085, significantly larger than the average RMSD for the fit of the FLMP.

One might wonder why a PPG model is necessary because bottom-up dominance could be built into the FLMP. However, the central assumption of

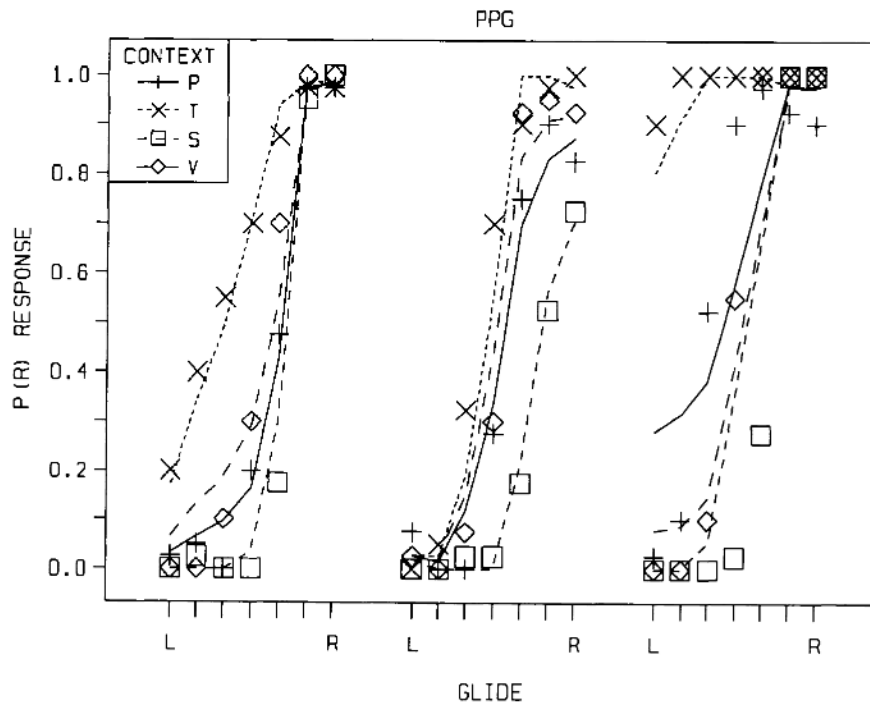


Figure 16.5 Observed (points) and predicted (lines) probability of *r* response for three typical subjects as function of glide F_3 onset level and context (after Massaro and Cohen 1983, experiment 2). Predictions are for PPG model.

the PPG model is qualitatively different from the FLMP. In the FLMP, both modalities are always integrated in speech perception, while only a single source is used on a given trial in the PPG model. That is, the response is either determined by the bottom-up information or by context when the bottom-up information is not identified. Thus the FLMP and PPG model provide distinctly different accounts of language perception. We will see that the PPG model also differs from another model grounded in modularity, namely, the RACE model.

16.9 RACE MODEL

Variations of a horse RACE model have been around for decades in a variety of guises such as the dual route model of reading. The version we consider is related to the one articulated by Cutler et al. (1987) and reinforced by McQueen (1991). In most speech-processing tasks, there are several possible routes to an interpretation of the input. In reading, for example, we can recognize a word directly from its orthographic form or by translating its letters into a speech code that is then used for lexical access. In another task involving spoken language, phoneme monitoring, subjects might report the occurrence of a phoneme either directly from the phonological level or indirectly from the spoken word containing the phoneme (Cutler and Norris 1979; Foss and Gernsbacher 1983). Similarly, in the Ganong lexical context task, the subject might report the first segment directly from the phonological representation or indirectly from the lexical activation or access of a particular word. The initial phoneme could be reported as voiced solely from the activation at the phonological level, or it could be reported from the activation of a lexical item. The route that is responsible for the judgment occurs probabilistically and is a function of task variables.

As emphasized by Frauenfelder, Segui, and Dijkstra (1990), the activation of the word via the lexical route occurs at a discrete moment in time, which also accepts the assumption that word recognition is all-or-none. In the spirit of a horse race, the RACE model also must assume that discrete information about the test segment (via the phonological route) is made available at a discrete point in time. This assumption stands in sharp contrast to the continuous sources of information available to the perceiver in the FLMP (Massaro and Cohen 1994). The RACE model appears to be related to a simple (perhaps too simple) quantitative account of the joint effects of stimulus and context. This model is the antithesis of integration, and has been called a "single-channel model" (Massaro 1985). It is necessarily assumed that only one of the two sources of information determines the response on any given trial. The emitted response is based on one source or the other. We define the probability of making a response on the basis of the initial segmental information as p . Given only two sources of information, and given that a response must come from one source or the other, the probability of making a response

on the basis of lexical information is $1 - p$. Thus predicted performance is given by

$$P(\text{voiced}|S_i \text{ and } C_j) = (p)(s_i) + (1 - p)g_j. \quad (16.6)$$

The value s_i is equal to the probability of a voiced decision made at the segmental level, and g_j is equal to the probability of a voiced decision made at the word level. The value i indexes the i th level along the stimulus continuum of the segmental information and j indexes the context. This formalization of the RACE model assumes a fixed p across all conditions, a s_i value that varies with the segmental information in the initial consonant, and g_j value that varies with the lexical context.

Advocates of the RACE model will quickly notice that equation 16.6 does not have the necessary complexity of verbal descriptions of the model. For example, p is expected to decrease to the extent the segmental information is ambiguous. In the Cutler and Norris (1979) model, the probability of making a decision on the basis of the segmental information depends critically on the relative speeds of the two routes. It seems reasonable to assume that the relative speed of the segmental route is an inverted U-shaped function of the levels of the segment between the voiced and voiceless alternatives. That is, the segmental route would be slow to the extent the segmental information is ambiguous. In this case, p should also depend on the level of segmental information. The subscript i is used to index the probability of responding on the basis of the segmental information (the prelexical route). Generalizing equation 16.6 gives

$$P(\text{voiced}|S_i \text{ and } C_j) = (p_i)(s_i) + (1 - p_i)g_j. \quad (16.7)$$

In this case, the value of p_i depends on S_i . To describe Pitt's results, this model requires 6 values of p_i , 6 values of s_i , and 2 values of g_j , for a total of 14 free parameters to predict just 14 independent data points. This makes the model untestable; there are no results using the Ganong task in which the full RACE model can be tested.

Because constraining the parameters of the RACE model did not seem justified, we are left with testing the model against the phonological constraints study. In this case, we simply envision that phonological constraints operate in the same manner in the RACE model as do lexical constraints. There are independent segmental glide and phonological admissibility routes and the winner is responsible for the response. Equation 16.7 was used to fit the results so that 7 values of p_i , 7 values of s_i , and 4 values of g_j , for a total of 18 free parameters to predict the 28 data points. As can be seen in figure 16.6, the RACE model gave a poor description of the results; the average RMSD was .085. Considering that the fit of the FLMP gave an average RMSD of .055, with just 11 rather than 18 free parameters, we have strong evidence for integration of bottom-up and top-down sources of information. Modular, strictly autonomous models are greatly damaged by the same results.

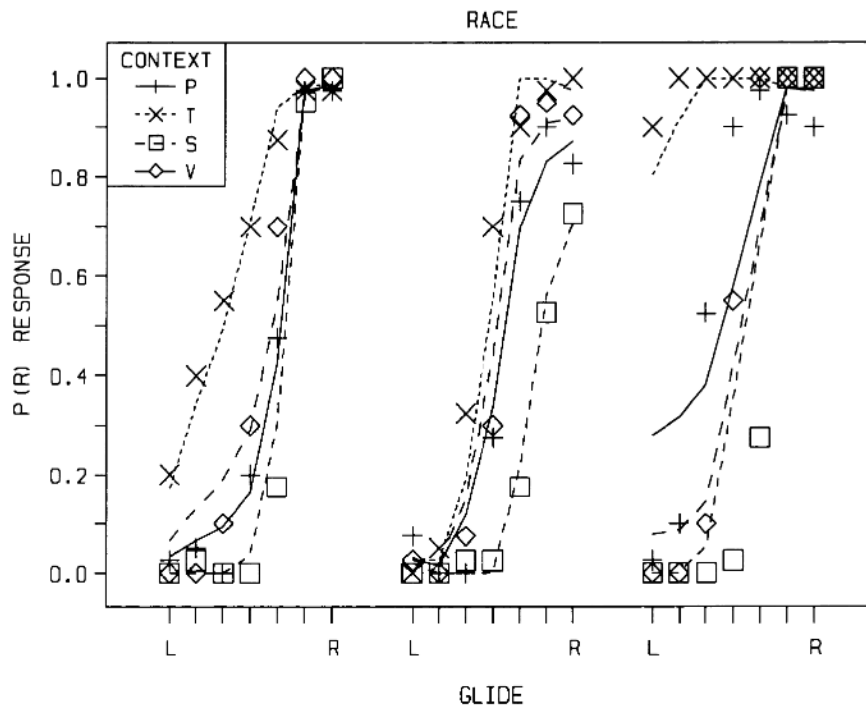


Figure 16.6 Observed (points) and predicted (lines) probability of *r* response for three typical subjects as function of glide F_3 onset level and context (after Massaro and Cohen 1983, experiment 2). Predictions are for RACE model.

16.10 INTEGRATING SENTENCE CONTEXT IN THE GATING TASK

The gating task (Grosjean 1980, 1985) has been a method developed to assess speech perception and word recognition. As indicated by the name of the task, portions of the spoken message are eliminated or gated out. Successive presentations involve longer and longer portions of the word; subjects attempt to name the word after each presentation. Warren and Marslen-Wilson (1987), for example, presented words such as *school* or *scoop*. The probability of correct recognition of a test word increases as additional word information is presented in the gating task.

The gating task appears to have promise for the investigation of speech perception and spoken language understanding. Investigators have shown that two features of the gating task do not limit its external validity. Multiple presentations of the test word on a given trial (Cotton and Grosjean 1984; Salasoo and Pisoni 1985) and unlimited time to respond in the task (Tyler and Wessels 1985) are not essential for the results. Thus the results appear to be generalizable to the on-line recognition of continuous speech.

Tyler and Wessels (1983) used the gating paradigm to assess the contribution of various forms of sentence context to word recognition. Subjects heard a sentence with its final word gated out. This test word was increased in

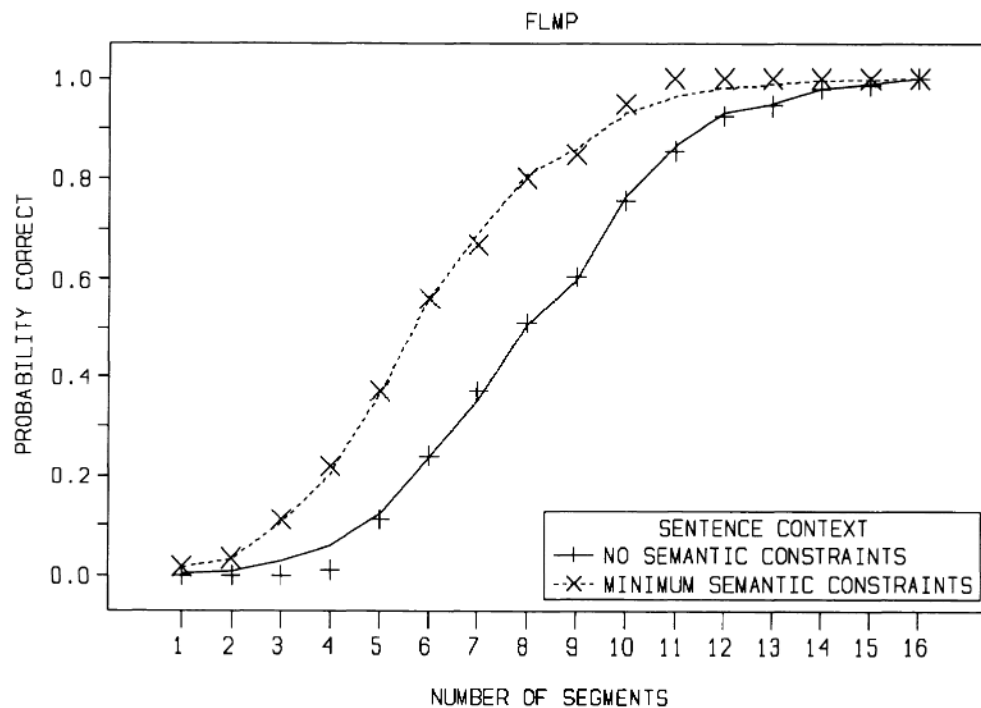


Figure 16.7 Observed (points) and predicted (lines) probability of identifying test word correctly as function of sentential context and number of segments of test word. Minimum semantic constraints refers to minimum semantic and weak syntactic constraints. No semantic constraints refers to no-semantic and weak syntactic constraints (results of Tyler and Wessels 1983; predictions of FLMP).

duration by adding small segments of the word until correct recognition was achieved. The sentence contexts varied in syntactic and semantic constraints. Some sentence contexts had minimal semantic and weak syntactic constraints in that the target word was not predictable in a test, given the sentence context and the first 100 ms of the target word. Performance in this condition can be compared to a control condition in which no semantic and weak syntactic constraints were present. If sentential context contributes to recognition of the test word, then accuracy should be better for the sentence context with minimum semantic constraints.

Figure 16.7 gives the probability of correct word recognition as a function the number of segments in the test word and the context condition. Both variables had a significant influence on performance. In addition, the interaction between the two variables reveals how word information and context jointly influence word recognition. Semantic constraints influence performance most at intermediate levels of word information. Their contribution is most apparent when there is some but not complete information about the test word. The lines in figure 16.7 give the predictions of the FLMP (see Massaro 1994). As can be seen in the figure, the FLMP captures the exact

form of the improvement in performance as a function of segmental information and sentential context.

As in the Ganong (1980) task, the PPG and RACE models would require more free parameters than data points in this study. Future studies should increase the number of context conditions in order to make the factorial design more symmetrical, and thus provide a test of these models with respect to the contribution of sentential context.

A positive effect of sentence context in this situation is very impressive because it illustrates a true integration of word and context information. The probability of correct recognition is zero when the minimum semantic context is given with very little word information (one segment). Similarly, the probability of correct recognition is zero with three segments of the test word presented after a sentence context with no semantic constraints. That is, neither minimum semantic constraints nor three segments are capable of producing a correct answer. Together, however, they allow a correct answer 1 out of 10 times; three segments of the test word preceded by a sentential context with semantic constraints produce about 10 percent accuracy. Although neither the semantic context alone nor the limited segmental information permits word recognition, when presented jointly, word recognition is above chance. This superadditive combination of bottom-up and top-down information is even more apparent when overall performance is intermediate. With seven segments, for example, semantic context improves accuracy from 40 to 70 percent. The superadditive combination of bottom-up and top-down information cannot be predicted by either the PPG or the RACE models because performance on any given trial must come from one source of information or the other. Thus the strong effect of minimum semantic context illustrated in figure 16.7 can be considered to reflect true integration of bottom-up and top-down sources of information.

The form of the interaction of stimulus information and context is also relevant to the prediction of the cohort model. Marslen-Wilson (1987) assumes that some minimum cohort set must be established on the basis of stimulus information *before* context can have an influence. In terms of FLMP description, this assumption implies that the output of the evaluation of context should change across different levels of gating. To test this hypothesis, another model was fit to the results; in this model, semantic context was assumed to have an influence only after some minimum gating interval. Because it is not known what this minimum interval should be, an additional free parameter was estimated to converge on the interval that gave the best description of the observed results. The model did not improve the description of the results, weakening the claim that semantic context has its influence only after some minimum stimulus information has been processed. This result is another instance of the general finding that there are no discrete points in psychological processing (see Tanenhaus et al., chap. 18, this volume, for analogous arguments). The system does not seem to work one way

at one point in time (i.e., no effect of context), and another way in another point in time (i.e., an effect of context).

16.11 NATURE OF INTEGRATION

The model tests have established that perceivers integrate top-down and bottom-up information in language processing, as described by the FLMP, which means that sensory information and context are integrated in the same manner as several sources of bottom-up information. The goal now is to address the nature of this integration process. Many investigators appear to believe that interactive activation is the only viable alternative to autonomous models. However, the FLMP allows integration while maintaining independence among the sources (at the evaluation stage). Because our concern has been with spoken language, I will discuss previous tests comparing the FLMP and a specific instantiation of interactive activation—the TRACE model.

16.12 INTERACTIVE-ACTIVATION—THE TRACE MODEL

The most popular form of integration is interactive activation. The TRACE model of speech perception (McClelland and Elman 1986) is one of a class of connectionist models in which information processing occurs through excitatory and inhibitory interactions among a large number of simple processing units. The units, arranged hierarchically, and putatively representing the functional properties of neurons, correspond to features, phonemes, and words. Features activate phonemes, and phonemes activate words, whereas activation of one type of units inhibits other units of the same type. In addition, activation of higher-order units activates their lower-order units; for example, activation of the word *gift* would activate the phonemes making it up.

A bottom-up source of information is processed sequentially through the feature, phoneme, and word units. Because of interactive activation, however, a top-down word context can modify the activation of the same lower-order units. Bottom-up activation from the phoneme units activates word units, which in turn, activate the phoneme units that make them up. Integration of bottom-up and top-down sources of information is achieved through interactive activation. Interactive activation appropriately describes this model because it is clearly an interaction between the two levels that is postulated. The amount of bottom-up activation modifies the amount of top-down activation, which then modifies the bottom-up activation, and so on.

In support of the TRACE model, Elman and McClelland (1988) carried out an ingenious demonstration of context effects in speech perception. Because of coarticulation—the influence of producing one speech segment on the production of another—a given speech segment has different acoustic forms in different contexts. The phonemes /s/ and /ʃ/ are necessarily produced differently, and will differentially influence the production of the following

speech segment. Perceivers not only recognize the different speech segments /s/ and /ʃ/; they apparently are able to compensate for the influence of these segments in recognizing the following speech segment. During production of speech, coarticulation involves the assimilation of the acoustic characteristics of one sound in the direction of the characteristics of the neighboring sound. The production of /s/ contains higher-frequency energy than /ʃ/ and coarticulation will give the sound following /s/ higher-frequency energy than the same sound following /ʃ/.

Perceivers apparently take this assimilative coarticulatory influence into account in their perceptual recognition of /t/ and /k/ (and /d/ and /g/). Mann and Repp (1981) showed that recognition of the same segment as /t/ or /k/ is dependent on whether the preceding segment is /s/ or /ʃ/. The energy in /k/ is somewhat lower in frequency than that in initial /t/—the /t/ has a high burst. Using synthetic speech, a continuum of speech sounds ranging from *tapes* to *capēs* was made by varying the onset properties of the sounds; these sounds were placed after the words *Christmas* and *foolish*. Subjects were more likely to identify the stop as /k/ than /t/ if the preceding fricative was /s/ than if it was /ʃ/ (for this contrast effect, see Mann and Repp 1981), a result that contributes to the validity of top-down effects on perceptual processing by making the hypothesis of a postperceptual decision less likely. There is no obvious guessing state based on the context that would produce the observed contrast effect.

Elman and McClelland's (1988) study induced the same contrast effect, mediated by the lexical identity of the first word rather than the acoustic structure of its final syllable. As expected from the Mann and Repp (1981) study, there were more judgments of *capēs* following *Christmas* than following *foolish*, although this dependency could have been triggered directly by the acoustic differences between /s/ and /ʃ/. To eliminate this possibility, Elman and McClelland (1988) created an ambiguous sound halfway between /s/ and /ʃ/ to replace the original fricatives in *Christmas* and *foolish*. Given a lexical context effect, we would expect that the ambiguous segment would tend to be categorized as /s/ when it occurred in *Christmas* and as /ʃ/ when it occurred in *foolish*. Would the same contrast effect occur given the same ambiguous segment in *Christmas* and *foolish*? Figure 16.8 shows that it did: subjects were more likely to report the test word *capēs* following the context word *Christmas* than following the context word *foolish*, and this effect was larger when the segmental information about the /k/-/t/ distinction in the test word was ambiguous.

Given interactive activation, the contrast effect can be described by assuming connections from the phoneme level in one time slice to the feature level in adjacent time slices (as in TRACE I, Elman and McClelland 1986, 1988). The units corresponding to /s/ and /ʃ/ phonemes would be connected laterally and downward to feature units, which in turn would be connected upward to the phoneme units /t/ and /k/. The downward activation from the fricative phoneme to the feature level would modulate the upcoming upward

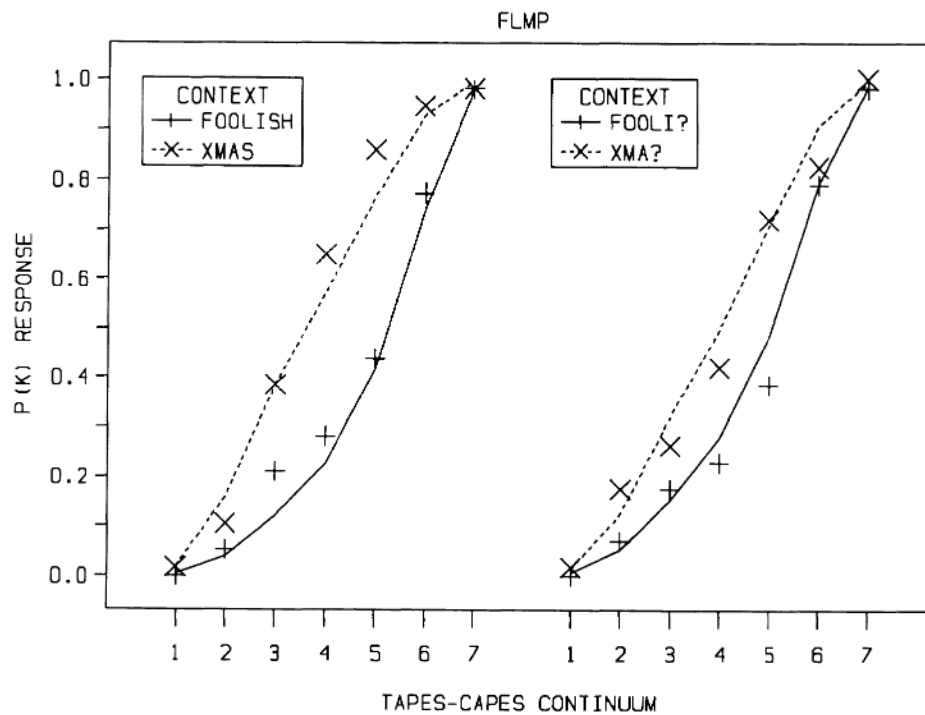


Figure 16.8 Observed (points) and predicted (lines) probability of /k/ identification as function of stimulus and preceding context for original and ambiguous preceding consonant. Results from Elman and McClelland (1988). Predictions are for FLMP.

activation from the feature level to the stop phonemes. To describe the lexical effect for the case in which the two words *Christmas* and *foolish* have the same ambiguous final fricative segment, top-down connections from the word level to the phoneme level would activate the appropriate phoneme unit—/s/ and /ʃ/ in *Christmas* and *foolish*, respectively. These units would then activate downward to the feature level, leading to a contrast effect. Because of the assumed top-down activation modulating the bottom-up activation, interactive activation is central to their explanation.

Description of the result does not require interactive activation, however. The result simply shows that information from the lexical level of the preceding word can influence the identification of the following word. Lexical context disambiguates the final segment of the context word, which in turn biases identification of the first segment of the following word. In this case, the top-down context influences the interpretation of the bottom-up information of the following segment. This perceptual bias has the same outcome as if the word context and the test segment function were two independent sources of information. Figure 16.8 gives the fit of the FLMP to the results (Elman and McClelland 1988, experiment 1; Massaro 1992). Nine free parameters were estimated to predict the 28 data points: 7 for the 7 levels along the

tapes-capes continuum, 1 for /s/ or /ʃ/ in the intact context word condition, and 1 for lexical context with the ambiguous final segment. The pure lexical context effect is seen in the left panel and the combined effect of lexical context and context segment (/s/ or /ʃ/) is shown in the right panel. The FLMP gave an acceptable description of the results, with an RMSD of .048. The good fit of the FLMP emphasizes the point that lexical context and segmental information can both contribute to word recognition *without* the context modifying the representation of the segmental information.

Because the context effects appear to be equally well accounted for by FLMP and by TRACE, it is important to test between them. The primary difference between TRACE and FLMP involves the joint effects of bottom-up and top-down information. The predictions of the models have been contrasted in the phonological constraints study described previously (Massaro 1989b; Massaro and Cohen 1991). Recall that subjects were asked to identify a glide consonant in syllables beginning with one of the four consonants /p/, /v/, /t/, or /s/ followed by a liquid consonant ranging from /l/ to /r/, followed by the vowel /i/.

A simulation of the phonological context experiment using TRACE was compared with the observed results (Massaro 1989b). A simulation of TRACE involves presentation of a pattern of activation to the units at the feature level. The input is presented sequentially in successive time slices, as would be the case in real speech. The processing of the input goes through a number of cycles in which all of the units update their respective activations at the same time, based on the activations computed in the previous update cycle. These activations are mapped into predicted responses, following McClelland and Elman (1986). Although the results of the simulation showed effects of both the bottom-up and top-down sources of information, the quantitative predictions of TRACE did not follow the form of the observed results (Massaro 1989b). These results might imply that interactive activation, the central premise of TRACE, is not a psychologically plausible mechanism for combining several sources of information.

More recently, several investigators have attempted to place the FLMP and the TRACE on more equal footing to allow more direct comparisons. One method has been to reduce the complexity of the TRACE by using miniature neural networks. A network designed to predict context effects is shown in figure 16.9 (McClelland 1991; Massaro and Cohen 1991). Three levels of units are assumed: "target," "context," and "word." The target and context levels can be considered to contain units activated by the target letter and the contextual letters, respectively; these are analogous to the bottom-up and top-down sources of information in the FLMP. Activation of context units and target units activates word units. Consistent with the TRACE assumption of interactive activation, all units within the context and target levels are bidirectionally connected to all word units. Only the excitatory connections are shown in the figure. Within each of the three levels, each unit also has inhibitory connections to all other units within that level.

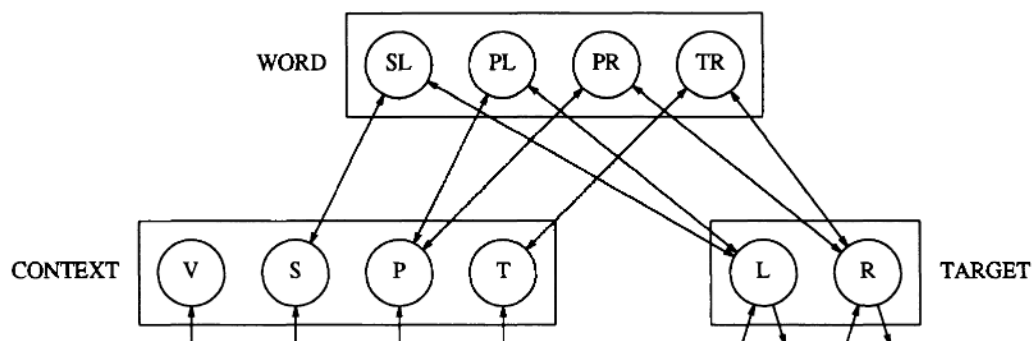


Figure 16.9 Network used in simulation of TRACE model applied to phonological constraints experiment of Massaro and Cohen (1983). Inhibitory connections between units within Word, Context, and Target levels are not shown in network.

The target units *R* and *L* are activated to varying degrees by the critical speech segment. As in the FLMP, we can assume that changes in the glide will change the activation of the *L* unit relative to the *R* unit. The context units are activated by the different contexts. The word unit labeled “*SL*” corresponds to all words that begin with /s/ and so on for the other word units. Because of the interactive-activation assumption, the word units in turn send their activation downward to the context and target units.

In the network, the effects of stimulus and context are combined via the units in the word layer. The activations of word units are fed back to the target and context units, changing their activations in a manner that reflects the activations of both target and context units. In this manner, the joint effects of target and context units are reflected in the activations of units in both the target and context layers. This passing of activation occurs for a number of cycles until a sufficient amount of activation occurs at the target units. The activations are mapped into strength values, which are then mapped into a response using the RGR.

The simplest model to fit to the study requires 11 parameters: 7 *R* target value inputs (with the *L* target receiving the additive complement), 4 context inputs (with the nonselected contexts set to 0). The simulation of the TRACE is completely deterministic; the outcome of a simulation under a given set of conditions will produce the same results each time the simulation is run. The TRACE outcome was fit to the observed data by minimizing the differences between the predicted and observed values. For each of the 28 experimental conditions, a simulation trial was run with a hypothetical set of parameter values, and a goodness of fit was computed. As in the fit of the FLMP, the parameter values were changed systematically to maximize the goodness of fit of the TRACE. As can be seen in figure 16.10, the TRACE is not capable of describing the influence of the different types of context, and does a poor job describing the results, with an average RMSD value of .083, significantly larger than the fit of the FLMP.

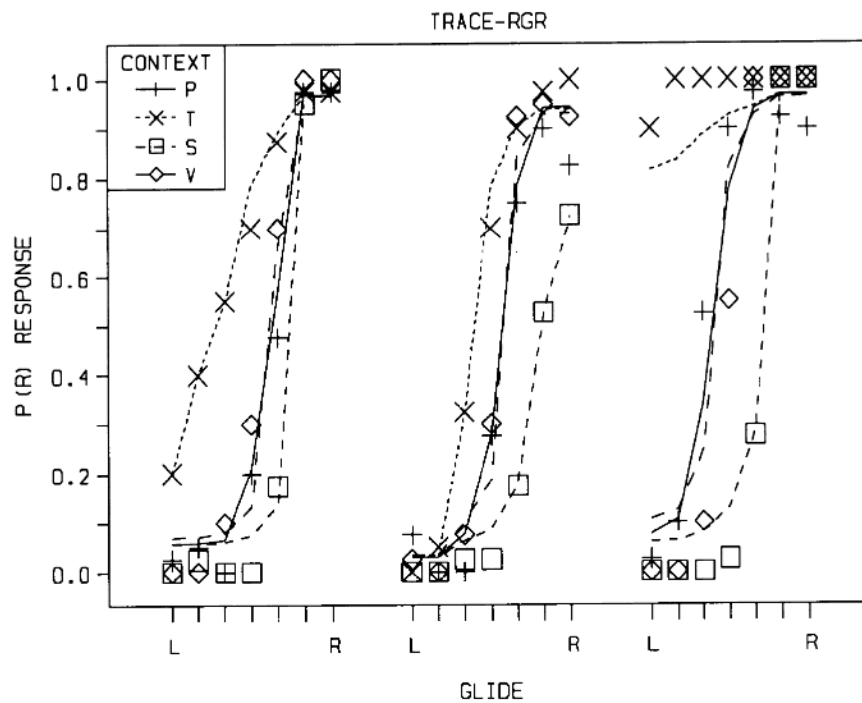


Figure 16.10 Observed (points) and predicted (lines) probability of *r* response for three typical subjects as function of glide F_3 onset level and context (after Massaro and Cohen 1983, experiment 2). Predictions are for TRACE model with RGR decision process.

McClelland (1991) placed the blame for the TRACE's failure to predict Massaro's (1989b) results on the decision stage of the model rather than on some other process such as interactive activation. The TRACE was modified by (1) adding noise to the inputs, thus making the initial processing in the model probabilistic rather than deterministic; and (2) changing the RGR decision rule to a best-one-wins (BOW) rule in which the response alternative corresponding to the most active unit would always be chosen (McClelland 1991). With these two modifications, McClelland (1991) argued that the predictions of the TRACE are consistent with the empirical observations (and with the predictions of the FLMP). However, this new model was not actually tested against any empirical results.

To provide an empirical test of the new TRACE, Massaro and Cohen (1991) ran simulation trials by adding normal noise samples to both the target and context input values. For each of the simulated trials, a BOW decision was made on the final target activations. The simulated trials gave the predicted proportion of responses at each of the experimental conditions. The fit of this model did not improve on the fit of the deterministic TRACE with the RGR decision rule. The RMSD obtained for this model was .111, about twice that found for the FLMP. Figure 16.11 shows the fit of this 11-parameter TRACE. A second, 12-parameter TRACE was run (starting with the parameters

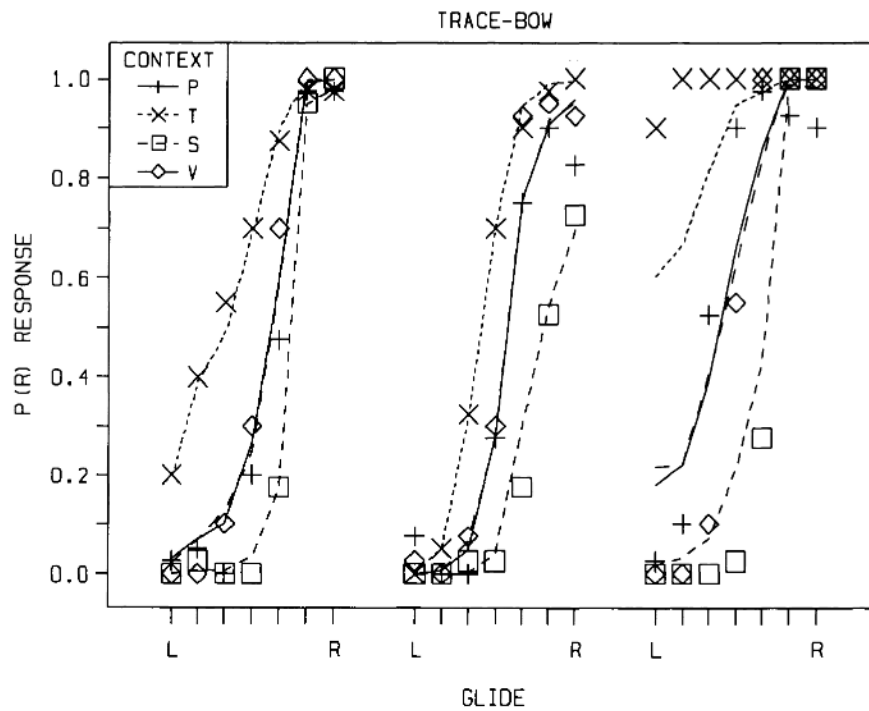


Figure 16.11 Observed (points) and predicted (lines) probability of *r* response for three typical subjects as function of glide F_3 onset level and context (after Massaro and Cohen 1983, experiment 2). Predictions are for TRACE model with BOW decision process.

of the 11-parameter model), which added the standard deviation of the noise as a free parameter. Only a small improvement was seen with an RMSD of .099, still significantly poorer than the fit of the FLMP. The TRACE model with intrinsic noise added at each processing cycle also gave a poor description of the results, relative to the FLMP. This model-fitting exercise shows that the FLMP gives a better description of the results than the TRACE; thus we can conclude these results support the FLMP over the TRACE.

Advocates of interactive activation, and researchers more generally, might not be easily persuaded by the differences in goodness of fit to empirical results. It is thus important to emphasize that interactive activation appears to have the incorrect dynamics to accurately describe the time course of perceptual processing. The influence of context necessarily lags behind the influence of bottom-up information in interactive activation models. However, there is strong evidence that context can have an influence at any time relative to the bottom-up information (Massaro and Cohen 1991). Moreover, interactive activation models must predict that context can eventually dominate bottom-up information with increases in processing, although this prediction fails empirical tests (Massaro and Cohen 1991) and goes against everyday behavior. If processing followed interactive activation, slow reading would permit top-down context to override bottom-up information. Readers slow down

to proofread, however, which makes the detection of misspellings easier to spot.

Other empirical results support the conclusion that interactive activation is not an appropriate process to account for the influence of context on perception (Massaro and Cohen 1991). One set of results comes from a phoneme monitoring task by Frauenfelder et al. (1990). They first found that reaction time (RT) to a target phoneme in a word decreased when the phoneme occurred near or after the uniqueness point—the point when only one word was consistent with the input up to that point. This result is consistent with the TRACE model because top-down activation from the lexical level would activate the word's phonemes. In a second study, they replaced one of the phonemes in the word with the target phoneme. Given that the word context should have activated the lexical representation in TRACE, top-down activation from the lexical level to the phoneme level should have occurred. Because of the lateral inhibition between phonemes, the target phoneme should have been inhibited and thus more difficult to detect. However, there was no increase in RT, even when the substituted phoneme differed by just the voicing feature. This result weakens TRACE's central assumptions about how activation and inhibition operate to combine top-down and bottom-up information. The results are consistent with the FLMP because there are no inhibitory processes in the model. A word context can facilitate processing of the segments making it up, but not inhibit the processing of other segments.

Another source of evidence against TRACE comes from McQueen (1991), who studied the influence of lexical context on the identification of a final segment, such as in *kiss-kish* and *fiss-fish*. Because top-down activation takes time to build up, TRACE predicts a larger context effect for slow responses than for fast responses for these syllable final distinctions. As also noted by Massaro and Cohen (1991), the presence of top-down activation requires several cycles of processing after activation from bottom-up sources; thus there would be less time for top-down activation with fast responses than with slow response, and a larger context effect should be found with slow responses. The actual results were just the opposite of this prediction: larger context effects with fast responses. These same results can be described by a dynamic version of the FLMP (Massaro and Cohen 1991; Massaro and Oden 1995). Lexical information and segmental information function as two sources of information processed continuously over time. When lexical context comes before the segmental information, there is more processing time available for the context, relative to the segmental information; in this case, fast responses are predicted to show a larger effect of lexical context than slow responses. On the other hand, when lexical context comes after the segmental information, there is *less* processing time available for the context relative to the segmental information; in this case, the FLMP predicts a larger effect of lexical context with slow, relative to fast, responses. These predictions hold up, as illustrated in McQueen's (1991) study with early lexical context and by Pitt's (1995) results with late lexical context.

Pitt (1995) used test items, such as /glft/ or /kls/, in which the lexical information occurs later in the test word than the phonological information in the initial consonant. The FLMP predicts that support for /g/ from the bottom-up and top-down sources grows with processing time, although there is necessarily a delay in the arrival of the lexical information, relative to the stimulus information from the initial consonant. To provide a quantitative test of this interpretation, the FLMP was fit to the 14 individual subjects and to the average results in Pitt's experiment 1. The model was fit to the three identification conditions in the slow, middle, and fast RT conditions. It was assumed that the available processing time differed in the three conditions. The available processing time was taken to be the mean RT for each subject under each of the three conditions; the mean RTs across the 14 subjects were 345, 445, and 663 ms, respectively. The mean RTs for individual subjects were taken to be the available processing time for the phonological information. These same values, minus a constant delay c_l , for the arrival of the lexical information, were taken to be the available processing time for the lexical information.

We assume that evaluation of the speech information follows the function in equation 16.8, which gives the amount of support s for /g/, defined as $S(s)$:

$$S(s) = \alpha(1 - e^{-\theta t}) + .5(e^{-\theta t}). \quad (16.8)$$

Equation 16.8 describes the evaluation process as a negatively accelerated growth function of processing time t ; it is assumed that the information provided by this source of information can be represented by α , and that the rate of processing this information, θ , is independent of the information value. The values of α , which represents the asymptotic support for the alternative /g/, are equal to the parameter values indicating the degree of support in the typical fit of the model when processing time is not a factor. If α corresponds to the amount of support for the voiced alternative /g/, then the speech syllable changed from a somewhat ambiguous /g/ to a less ambiguous /g/ would have a larger α value but would be processed with a fixed θ . The three RT conditions would necessarily have different processing times. The same type of equation would describe the growth of the lexical context information c , except that the constant delay c_l for its arrival would be subtracted from the available processing time.

Integration of the outputs of evaluation occurs continuously, producing a overall goodness of match for each of the test alternatives. Given two sources of information, the output of integration, $S(s, c)$, is given by equation 16.9:

$$S(s, c) = [\alpha_s(1 - e^{-\theta t}) + .5(e^{-\theta t})] \times [\alpha_c(1 - e^{-\theta(t-c_l)}) + .5(e^{-\theta(t-c_l)})], \quad (16.9)$$

where α_s is the asymptotic support from the initial consonant stimulus and α_c is the asymptotic support from the lexical context. The value of θ is assumed to be the same for both the stimulus information and the lexical context and c_l is the delay between the onset of the processing and the onset of the lexical

information. The RGR at decision is simply instantiated when the feature evaluation and integration are completed, as constrained by the RT condition. The same operations occur at all 3 RT conditions; only the available processing time differs across the conditions.

To provide a baseline for the fit of this dynamic FLMP, the FLMP was first fit to each of the three RT conditions separately, with a unique set of 10 parameters for each RT condition. The average RMSD for the fit of the 14 individual subjects was .017, whereas the RMSD for the fit of the average subject was .010. Thus the static FLMP provides an excellent description of the results. The fit of the dynamic FLMP reduces the number of free parameters from 30 to 12; in this case, the FLMP is being tested against three times as many data points (16 versus 48 observations) with only 2 additional parameter values (θ corresponding to the rate of processing and c_i). Figure 16.12 gives the predictions of this dynamic FLMP to the average results; as can be seen, the dynamic FLMP nicely describes the increase in the influence of lexical context with increases in processing time. The average RMSD for the fit of the 14 individual subjects was .046, whereas the RMSD for the fit of the average subject was .020. Considering the savings in the number of free

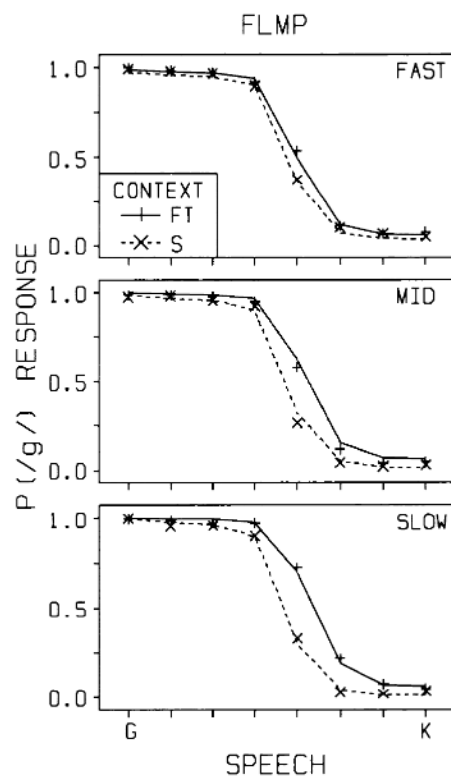


Figure 16.12 Observed (points) and predicted (lines) proportion of /g/ identifications for /ft/ and /s/ contexts as function of speech information of initial consonant. Three panels give results for fast, middle, and slow identifications. Predictions of FLMP.

Table 16.1 Domains of Language Processing That Provide Evidence for FLMP

Domain	Sources of Information
Speech perception	Acoustic features
	Visible speech
	Gesture
	Tactile speech
	Electrical speech
	Phonological constraints
	Lexical constraints
	Syntactic constraints
	Semantic constraints
Reading	Letter features
	Orthographic constraints
	Lexical constraints
	Spelling-to-sound constraints
	Sentential constraints
Sentence Interpretation	Semantic information
	Syntactic information
	Prosodic information

parameters, the dynamic FLMP does a respectable job of describing the results. The average value of θ was 8.59 and the average value constant delay c_l was 297 ms. It is encouraging that the value of c_l is a reasonable estimate of the time between the onset of the syllable and the onset of the lexical context. The good description given by the dynamic FLMP reveals that the influence of lexical context as a function of RT is most parsimoniously described as due to processing time. Postulating different strategies or some other qualitative influence is not necessary.

Although we have been concerned with empirical results from only a few domains, it is important to remind the reader that there is evidence for the FLMP framework from a much broader set of domains. Table 16.1 lists the domains of language processing that provide evidence for the FLMP. Supporting results come from reading as well as from spoken language, and also from the more cognitive task of sentence interpretation (Bates and MacWhinney 1987). As can be seen in the table, the FLMP has been able to account for the influence of a broad range of information sources in language processing.

16.13 PARALLELS IN VISUAL PERCEPTION

In vision, the perceiver's goal is to solve the problem of what environmental situation exists, given the current conflux of sensory cues. This conceptualization of visual perception is exemplified by several authors in this volume (see Bülthoff and Yuille, chap. 3; Frisby, Buckley, and Freeman, chap. 4). Their work is based on the assumption that the combination or integration of

several depth cues or visual modules is fundamental for successful visual processing. The Bayesian framework of Clark and Yuille (1990) used by Bülthoff and Yuille is in many ways analogous to the framework used in our research. It is striking that two very similar frameworks would be developed in very different domains—claimed to fundamentally different modules (Fodor 1983). As we have seen, the language-processing literature is consistent with the idea that the cues are first treated independently before being integrated to achieve perceptual recognition. Bülthoff and Yuille, (chap. 3), on the other hand, argues for some type of stronger coupling between the cues supporting vision. In Clark and Yuille's (1990) terms, strong coupling implies that "the operation of one sensory module is affected by the output of another sensory module so that the outputs of the two sensory modules are no longer independent" (p. 72). We have yet to see convincing evidence of strong coupling in vision, whereas some research clearly supports the assumption of cue independence (Cutting and Bruno 1988; Massaro 1988; Massaro and Cohen 1993).

Bülthoff and Yuille (chap. 3, this volume) use results such as those shown in figure 3.5 of their chapter as evidence for strong coupling. The results are interpreted to mean that the combination of two cues produces more accurate perception than could be predicted from the two cues. Stated another way, perception of shape, given each cue presented alone, is too poor to account for the accurate shape perception, given both cues. The implicit assumption in this interpretation is that one of these cues can be presented without the other, for example, shading can be presented without texture; however, a shape will always have some information about texture and shading (see Massaro 1988 for a more thorough description of this point). It is simply the case that the presentation of a single cue actually involved presentation of the other cue, but at a value that supported the "incorrect" frontoparallel projection. From this perspective, the poor shape judgments in the "single-cue" conditions reflect the integration of two opposing cues; it follows that the good shape judgments, given two consistent cues, do not demand a "strong coupling" interpretation.

16.14 PHENOMENAL EXPERIENCE IN LANGUAGE PROCESSING

Psycholinguistics is perhaps too wedded to our phenomenal experience in seeking explanations. One phenomenal experience in speech perception is that of categorical perception. Listening to a synthetic speech continuum of syllables varying between /ba/ and /pa/ provides an impressive demonstration: students and colleagues usually agree that their percept changes qualitatively from one category to the other in a single step or two, with very little fuzziness in between. Another misleading impression is that we hear substantial silent periods between the words of an utterance, when in fact very little silence exists. We also wonder, regardless of our native language, why foreign languages do not have these silences, whereas our language does; we

impose our speech categories on other languages. This author has had several experiences of hearing certain German, Spanish, and Japanese phonological categories in terms of similar English ones. Our phenomenal experience, however, may reveal very little of the hidden processes supporting perception and understanding. As noted by Marcel (1983), phenomenal experience might be dependent on linking current hypotheses with sensory information. If the sensory information is lost very quickly, continuous information could participate in the perceptual process but might not be readily accessible to introspection. As in most matters of psychological inquiry, we must find methods to tap the processes involved in cognition without relying on only introspective reports.

Dennett (1991) has clarified an important distinction between “filling in” and “finding out,” which is highly relevant to our phenomenal experience of categorical perception. In the categorical perception viewpoint, there seems to be significant filling in: we perceive two different speech events as the same category because a speech-is-special module makes them equivalent at the sensory/perceptual level. On the other hand, it is possible that categorization is simply finding out. That is, the goal of speech perception is categorization; we are able to find out which category best represents the speech event without necessarily modifying the sensory/perceptual representation of that event. In terms of the FLMP, we evaluate, integrate, and make a decision, if necessary, without necessarily modifying the sensory/perceptual representations of the speech event.

Perceptual effects can arise from sources of information other than the modality in question. For researchers like myself who spend a good deal of time looking at a talking face as well as listening to it, the most convincing result is that the speaker’s face influences our “auditory” perceptual experience (McGurk and MacDonald 1976). I interpret this type of influence as analogous to the influence of top-down sources of information in speech perception (Massaro 1994). Although a strong interpretation of autonomous processing might argue that auditory perception should not be penetrated by visual information, visual information and auditory information are integrated to achieve perceptual recognition. Analogously, the experimental results described in this chapter show that bottom-up and top-down sources of information are integrated in word and sentence processing.

Filling in might appear to be an attractive explanation of our phenomenal experience of contradictory auditory and visual speech. We are told to report what we hear, and the visible speech biases our experience relative to the unimodal auditory case. Because it is our auditory experience we are reporting, it seems only natural to believe that the representation of the auditory speech has been changed—filled in—by the visual. Another interpretation, however, is that we do not have veridical access to the auditory representation. As Marcel (1983) has pointed out, we report interpretations—finding out—and not representations. Thus we must be careful about equating phenomenal reports with representations.

Not only can we be misled by our perceptual experience, we also are fallible with respect to our understanding of language. The illusion of knowing has been well documented (Glenberg et al. 1987). Students are asked to read a passage and indicate if they understand it. They read it and then claim it is perfectly clear—even though the passage contains a blatant contradiction. They presume knowledge and coherence when in fact there is very little. The same might be said of our reaction to political speeches. We too often nod our heads in agreement in circumstances where we do not know what we are agreeing with. This takes our interpretation of the Japanese “yes” or nod of agreement one step farther. Westerners have learned that “yes” from a Japanese does not mean their listener agrees—only that he or she understands. We must also realize that “yes,” or even an apparently informed answer from any listener, might not signify understanding, as in our illusory understanding of the Moses question.

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