Journal of Psycholinguistic Research, Vol. 28, No. 4, 1999

Categorization of Ambiguous Sentences as a Function of a Changing Prosodic Parameter: A Dynamical Approach

Joanna Rączaszek,[1,3] Betty Tuller,[1] Lewis P. Shapiro,[2] Pamela Case,[1] and Scott Kelso[1]

The present study investigates the dynamics of changes in interpretation of ambiguous sentences. The sentences used had alternative interpretations with different surface structures (bracketing). Continua were created by systematic manipulation of prosodic cues (relative foot duration), resulting in stimulus sentences that spanned the range between the two interpretations. Continua were presented to subjects who were requested to indicate as quickly as possible which meaning they perceived. The pattern of responses and response times revealed the presence of hysteresis. That is, when the values of prosodic parameters are congruent with both interpretations, the individual's recent history decides which meaning will be perceived. Thus, we can treat this categorization process as a transition from an initially stable meaning that loses stability with variations in prosody (our control parameter). The same underlying dynamics have been observed in studies of perception of syllables and aspects of visual perception. Apart from demonstrating the same characteristics of pattern formation at various levels of cognition, the study points to the usefulness of the dynamical approach in the investigation of language understanding.

Recent linguistic theories and psycholinguistic research treat a sentence as a complex structure that results from many local computations (Chomsky, 1995; Frazier & Clifton, 1995). Thus, experimental work uses various on-line techniques (for example, Cross Modal Lexical Decision task, naming, Stroop task) to examine local processes and information present at specific

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The present work was supported by NIMH grant MH42900, BRS grant RR07258, and NIH grant DC 00494.

[1] Center for Complex Systems and Brain Sciences, Florida Atlantic University, Boca Raton.
[2] Department of Communicative Disorders, San Diego State University.
[3] Address all correspondence to Joanna Rączaszek, presently at Department of Psychology, Warsaw University, ul. Stawki 5/7, 00-183 Warsaw, Poland.

0090-6905/99/0700-0367$16.00/0

points of an unfolding sentence. The processes involved are sometimes assumed to be exclusively language-specific computations performed on representations of specifically linguistic information.

In contrast to this incremental approach, some theories emphasize the top-down effects coming from the larger, more complex structures [e.g., word superiority effect (Solman, May, & Schwartz, 1981); Interactive Activation Model (McClelland & Rumelhart, 1981), etc.]. Both local processes and final interpretation seem to be influenced by these effects. Not denying the importance of local, incremental processing, in this work we examine global processes in sentence understanding and propose that their characteristics indicate general organizational properties of cognitive systems and thus may not be specific to linguistic stimuli. Specifically, we claim that the effects observed in perception of sentential meaning are common to perceptual phenomena in general and may stem from the underlying dynamics of a cognitive system.

Extracting meaningful structures or patterns from impinging stimuli is a crucial ability in cognitive functioning. Various cognitive tasks are used to elucidate the nature of this process, one of the most prominent being categorization. In this task researchers attempt to determine what physical characteristics of a stimulus are necessary and sufficient to include a token into a category, i.e., what parameters and what values of these parameters define the categories. The studies range from simple physical stimuli such as colors (Beare, 1963; Boynton & Gordon, 1965) or tones, to categorization of complex objects into natural or artificial classes (e.g., Liberman, Harris, Hoffman, & Griffith, 1957; Bruner, 1973). Most of this research involves random presentation of the stimuli from a continuum created by systematically manipulating a parameter. The dependent measure is the frequency with which subjects classify each stimulus as a member of a given category. Typically, subjects reliably assign stimuli from one end of the continuum to one category and stimuli from the other end of the continuum to the other category. Stimuli that have intermediate parameter values are classified to one or the other category with certain probabilities. The result is a sigmoidal identification function in which the y axis represents the probability of including the stimulus in one category and the x axis represents the values of the manipulated parameter (Fig. 1). That the boundary between categories is sigmoidal and not square is usually interpreted as stemming from the inaccuracies of the perceptual system or from noise.

Recently, however, a new approach has emerged which proposes that the sigmoidal shape of identification function is not due to unpredictable random effects but rather can be explained by the dynamics of the cognitive system interacting with the stimuli. New methods have been created to elucidate the systematic effects stemming from this dynamics (Tuller, Case, Kelso, & Ding, 1994).

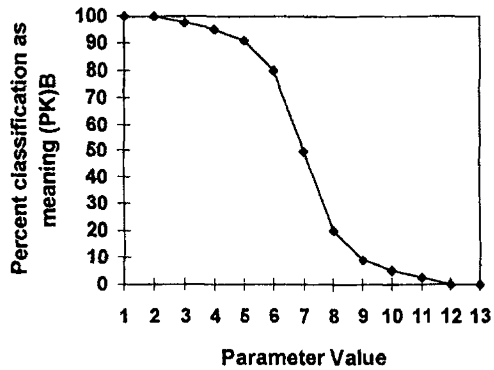

Fig. 1. Typical identification function.

The traditional methods, by randomizing stimuli, eliminate sequential effects and forfeit the possibility of observing the long-range dynamics of perception (i.e., those effects ranging over several stimuli). In the dynamical approach it is argued that responses in the intermediate range of parameter values can be accounted for by adaptive flexibility of perception—flexibility that stems from the dynamics that underlie performance. In this framework the characteristics of the system can be most readily identified during transitions from one state to another. The method used consists of sequential rather than random presentation of stimuli from a continuum spanning at least two categories. Subsequently, the properties of the transition are studied, using mathematical tools developed originally in physics for studying pattern formation in open nonequilibrium systems. The dependence of the characteristics of pre- and posttransition perception on both the physical parameters of the stimulus and on the internal properties of the cognitive system can then be elucidated. This approach has been applied successfully in studies of perception of various stimuli, which are (by traditional information-processing theories) considered "computationally simple" (see e.g., Hock, Kelso, & Schöner, 1993; Tuller et al., 1994; Kelso, Case, Holroyd, Horvath, Rączaszek, Tuller, & Ding, 1995). In the following set of experiments, we seek to determine if similar dynamics, with notions of pattern coherence, multistability, order parameters, control parameters, etc., apply to processing of complex linguistic stimuli (sentences). In other words, we ask if the effects observed in the categorization of sentential meaning support the view of meaning perception as cognitive pattern formation.

To make our position clear: We do not claim that in understanding a sentence, local, incremental (possibly automatic and possibly modular) processes do not take place. Rather we chose to focus on the putative influence of more global organizational principles. The issue of the interplay between the two (i.e., if the local processes are governed by or rather stem from the global organization), although a very interesting one, exceeds the scope of the present work. Here we seek to demonstrate that general organizational laws are at work in sentence comprehension. Such a view gives us a new way of characterizing the processes of sentence understanding. Focusing on the concept of stability and instability of perceptual organization allows us to exploit the tools of nonlinear dynamical systems theory and to construct relatively low-dimensional models of the cognitive process (i.e., models in which the number of variables sufficient to describe important behavioral characteristics is relatively small). Such models can be a fruitful source of novel predictions. Furthermore, in a model of sentence comprehension, the coherence of the global sentential structure can take the role of a driving force of contextual adaptation of the locally available information. This idea seems to be a promising way of getting rid of (often mysterious) active agents (or homunculi) from the mechanisms of sentence processing.

Treating perception of linguistic stimuli as a dynamical pattern formation process relies on a certain view of perception that needs to be (at least briefly) made explicit.

PERCEPTION AS PATTERN FORMATION

The dynamical approach stems from accounts of self-organized pattern formation in open nonequilibrium physical systems by, e.g., Haken (1983) and Nicolis and Prigogine (1989) but has recently been adopted by some researchers as a useful framework for the behavioral sciences (e.g., Haken, 1990; Kelso & Schöner, 1987; Kelso, 1984, 1990, 1995; Schöner & Kelso, 1988; Turvey, 1990). The initial focus is on examining how coherent patterns form and change under systematic variations of a nonspecific "control parameter." Underlying processes are most readily identified near transitions, where it is postulated that a new behavior or percept arises as a result of the loss of stability of one coherent behavioral state along with the availability of new stable states. Although a very large number of factors may influence a transition, and many elements are typically involved, it has been demonstrated that near such instabilities the system's behavior may be described by low-dimensional equations of motion (Haken, 1983). Experimental observations have repeatedly confirmed predictions regarding changes in relative stability of the patterns on the basis of various measures (see, e.g., Jeka & Kelso, 1989; Kelso et al., 1995, for many examples and a recent review).

This approach has been fruitful for over a decade in the movement sciences (Beek, 1989; Haken, Kelso, & Bunz, 1985; Kelso, 1984; Schöner & Kelso, 1988; Turvey, 1990) and has been extended to perception–action coordination (Kelso & Kay, 1987; Kelso, DelColle, & Schöner, 1990; Schmidt, Carello, & Turvey, 1990) and, recently, to perception itself (Hock et al., 1993; Tuller et al., 1994). In the case of perception, coherent patterns that correspond to perceiving a stimulus are characterized in terms of their persistence, stability, and change. Nonlinear transitions of patterns brought about by smooth changes in a control parameter make it possible to investigate predictions about the measures of these characteristics.

In the present study we pioneer the use of such a methodology in the perception of complex linguistic stimuli. In order to observe if the changes in meaning perception are due to changes of stability, we needed to find a control parameter that, when varied, leads the listener from one meaning to another. After this nontrivial step, we can investigate behavior before, at, and after the point of transition and observe possible pattern disintegration and pattern formation processes closely.

For this purpose we used ambiguous sentences, i.e., sentences that have more than one possible interpretation. Sentences considered by linguists and psycholinguists to be ambiguous are rarely perceived as such in everyday usage. Usually in understanding spoken sentences, linguistic or situational context plays a significant role in disambiguation. The interpretation of sentences, or perception of meaning, is biased by the existing situation. Sometimes, however, such context is not available or is not sufficiently clear to disambiguate the meaning. Under those circumstances, interpretation of a sentence may be based on prosodic information. There are many different acoustic cues that are used to demarcate phrase boundaries (see, e.g., Liberman & Prince, 1977; Lehiste, 1973; Price, Ostendorf, Shattuck-Hufnagel, & Fong, 1991; Scott, 1982; Nagel, Shapiro, & Nawy, 1994; Nagel, Shapiro, Tuller, & Nawy, 1996) including modification of fundamental frequency contour, stress, or pronunciation of phrase-ending stop consonants, as well as modification of timing of particular words and phrases (i.e., pauses in the phrase boundaries and length of the phrase-final vowel).

In our experiment we excluded external (linguistic, situational) context as a means of disambiguation and focused on prosodic information, which is more amenable to systematic manipulation. Not all ambiguous sentences can be easily disambiguated by such information. For example, Lehiste (1973) points out that when a sentence in its different meanings preserves its phrase boundaries (i.e., bracketing), prosodic cues are not very helpful in conveying the right meaning. In contrast, sentences that have different surface structure in alternative meanings, i.e., different bracketing, can be successfully disambiguated by prosody.

For example, the sentence:

"He won over his enemies."

has phrase boundaries in different places for the two alternative meanings.

"He [won] [over his enemies]."

when the intended meaning is that he fought and beat his enemies, and

"He [won over] his enemies."

when the intended meaning is that he persuaded his enemies to be on his side. It is these boundaries that speakers make clear during production of a sentence by the intonation and timing of particular words and phrases. After examining the relative role of intonation and timing, we concluded that timing is often sufficient to change the perception of ambiguous sentences from one meaning to the alternative. A considerable body of research has confirmed the important role of duration in disambiguation of sentences by marking phrase boundaries (e.g., Lehiste, 1973; Price et al., 1991; Scott, 1982).

In our experiments, the specific temporal manipulation consisted of changing the duration of the pause at the phrase boundary and the duration of the vowel in the stressed syllable before the boundary, which resulted in a change of relative foot duration of a sentence (see below for details). Unlike in other studies on prosodic disambiguation (e.g., Scott, 1982; Nagel et al., 1996), we did not set the fundamental frequency contour to a constant value (monotony). We wanted subjects to perceive natural sentences in which all other cues were preserved in order to see if and how the perception of a global pattern changes when driven by a single control parameter. If the transition is indeed a result of underlying dynamical processes, then it should demonstrate properties characteristic of phase transitions in open dynamical systems. In such cases the global pattern (the meaning of a sentence) is captured by a collective variable, or order parameter, and the process of meaning change by the dynamics of this order parameter. Since the order parameter acts back on the components of a dynamical system, the other cues are expected to be, in a sense, enslaved (Haken, 1983), even if they bias against the perceived meaning. In other words, once the meaning is perceived as the alternative, these other cues are incorporated in a new pattern.

To summarize: we have identified a parameter (relative foot duration) that has the potential of leading the listener from one interpretation of an ambiguous sentence to another. Sequential presentation of stimuli enables the control over direction and recent context of the change. We seek to determine if the contextual effects observed during the transition justify treating perception of sentence meaning in dynamical terms of a pattern formation process. Such an interpretation allows conceiving alternative meanings of a sentence as stable regions of the dynamics of a perceptual system.

EXPERIMENT 1

In this experiment sentences with a varying prosodic parameter are presented first sequentially then randomly. In the sequential condition there are three possible outcomes or response patterns: hysteresis, critical boundary, and enhanced contrast. These patterns are illustrated in Fig. 2.

For a trial in which the prosodic parameter is first systematically increased and then systematically decreased, hysteresis means that the subject remains longer in the initially perceived interpretation, i.e., the switch to the alternative sentence interpretation will occur at a larger parameter value when it increases than the switch back to the initial meaning when the parameter value decreases. Critical boundary is observed when the switch between alter-

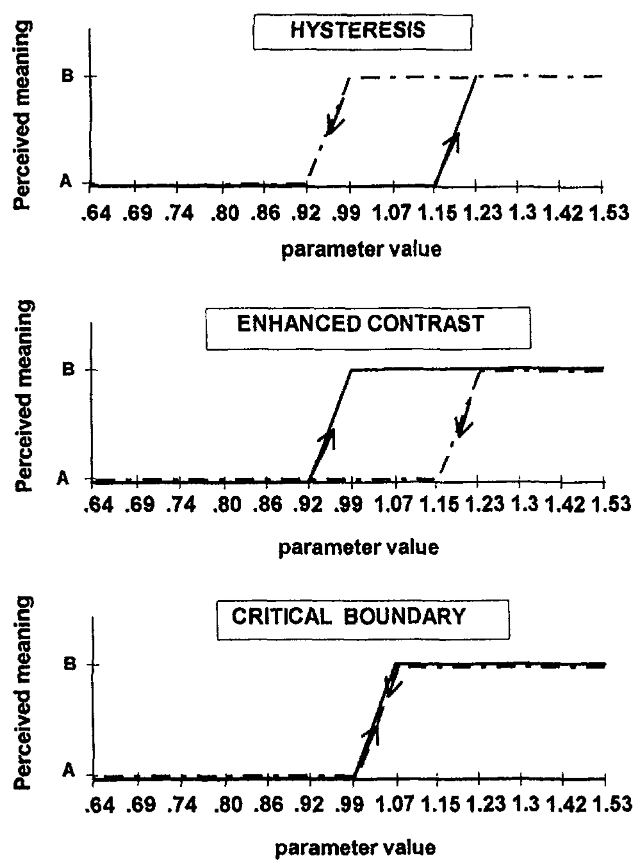

Fig. 2. Patterns obtained in sequential presentations of stimuli from a parameter continuum: hysteresis (top), enhanced contrast (middle), critical boundary (bottom). A, B: alternative meanings; solid line: ascending part of the run, dashed line: descending part of the run.

native sentence meanings occurs at exactly the same parameter value regardless of the direction of change of the parameter. In enhanced contrast, the switch on the way up occurs at the smaller parameter value than the switch on the way down.

If the perception of ambiguous sentences depended only on the value of the durational parameter, then the critical boundary pattern should be the most common. If, on the other hand, perception of sentence meaning can be conceptualized as a pattern-formation process, we should observe similar systematic dependence on recent history as seen in the perception of other stimuli (e.g., Tuller et al., 1994). Therefore we expect that patterns of hysteresis and enhanced contrast will be much more frequent than critical boundary. Both hysteresis and enhanced contrast indicate that, for the same value of the prosodic parameter, two different meanings of a sentence can be perceived, i.e., that two possible stable perceptual organizations coexist (multistability) and that previous judgments influence which one will ultimately occur.

Material

After a careful selection process,[4] one sentence was chosen based on how clearly the temporal measure differed between alternative productions. The sentence used was:

"Pat or Kate and Bob will come."

There are two possible interpretations. The first one, henceforth designated P(KB) is:

"[Pat] or [Kate and Bob] will come."

and the second, which will be designated (PK)B is:

"[Pat or Kate] and [Bob] will come."

[4] This sentence was chosen out of a set of 7 ambiguous sentences. Each sentence was read aloud by 2 speakers both in a discourse context biasing it toward one possible interpretation, and in the context biasing it toward the alternative interpretation. Speakers were asked to read naturally, without undue emphasis. Speakers also read the sentences in isolation. In that case the meaning that we wished a speaker to convey was written beneath each sentence and speakers were asked to stress the differences between alternative meanings. All sentences were recorded onto tape for later digitization and computer analysis.

Alternative meanings of the ambiguous sentences clearly differed with respect to pauses and vowel durations both in normal and exaggerated versions. The sentence chosen was among ones that differed most clearly and were not voiced throughout, which would have made insertion of pauses more problematic.

Both productions were obtained from a male speaker who read the following two passages:

> " 'Who is going to be at your party?'
> 'I am not sure yet. I would like to ask Kate and Bob but I would also like to see Pat.'
> 'Why can't you invite all three of them?'
> 'They can't stand each other! Especially Bob and Pat don't like each other. So Pat or Kate and Bob will come.' "

for the P(KB) interpretation, and

> " 'Do you know who is going to be at the party?'
> 'I don't know for sure—I know that Bob will come. Pat and Kate cannot both come because one of them has to stay home with their kid. So Pat or Kate and Bob will come.' "

for the (PK)B interpretation.

Notice that the alternative interpretations differ in presence or absence of two phrase boundaries (one after "Pat" and another after "Kate"). Studying the same syntactic construction, Scott (1982) determined that one of the factors that effectively influences the choice of interpretation is the relative duration of the so-called "feet." For the purpose of this work we will consider a foot to be a string of syllables that begins with an accented syllable and extends to another accented syllable. So in our sentence there are four feet: 1: "Pat or," 2: "Kate and," 3: "Bob will," 4: "come." What varies in alternative interpretations is the ratio of the first foot duration to the second. The duration of last stressed vowels before boundaries and of pauses as well as the ratio of Foot 1 to Foot 2 in alternative productions are given in Table I.

The foot ratio of each production was systematically manipulated so that it approached that of the alternative interpretation in 12 equal logarithmic steps. The ratio was manipulated by extending one foot [the first one in the (PK)B interpretation and second one in the P(KB) interpretation] by making the last stressed vowel longer and lengthening the pauses at the boundary, while at the same time shortening the other by making the last

Table I. Durations of Stressed Vowels, Pauses, and Foot Ratio for Each Production

	Meaning (PK)B	Meaning P(KB)
Vowel in "Pat" (ms)	168	278
Pauses after "Pat" (ms)	0	50
Vowel in "Kate" (ms)	263	144
Pause after "Kate" (ms)	77	0
Foot 1/Foot 2	.64	1.53

stressed vowel and the pause before the boundary shorter. In order to make a vowel longer, we iterated a single central pitch pulse in subsequent steps. In order to make it shorter, we eliminated pitch pulses. Since the change in length of a vowel could be done only in discrete steps (of the length of a pitch pulse, i.e., about 7 ms) the excess or deficit was compensated by changes in pause length. In this way we obtained 26 stimuli (the two original productions and 12 altered versions of each). An example of such a transformation is shown in Fig. 3.

In Fig. 3a we see the original version of the sentence produced to convey meaning (PK)B, and in Fig. 3b, the original production of meaning

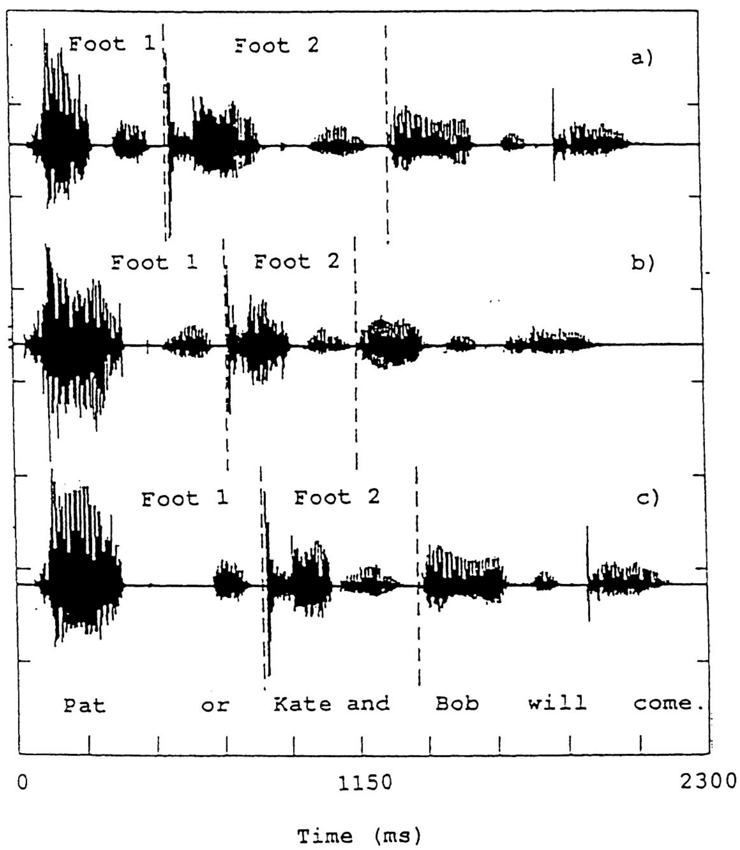

Fig. 3. Digitized sentences: (a) The original version of "(Pat or Kate) and Bob will come." (b) Original version of "Pat or (Kate and Bob) will come." (c) Altered version of sentence (a) toward the alternative meaning.

P(KB). Notice the different proportions of Foot1 to Foot2. Figure 3c depicts the last (12th) transformation of the sentence in Fig. 3a. One can observe that the proportions of Foot1 to Foot2 are more similar in Figs. 3b and 3c than in Figs. 3a and 3c.

Sequences of sentences were constructed that: (1) started from the original version, changed toward the most manipulated version (that had the foot ratio of the alternative meaning), and then returned to the original (26 stimuli); and (2) started from the manipulated version, changed toward the original and back (also 26 stimuli). This was done for both productions of the sentence (in both of the meanings). A set of 70 randomly ordered sentences from one of the continua [(PK)B] also was created, which included 10 instances of every other sentence from the continuum.

Procedure

In order to establish subjects' initial preferences for interpretation of the sentence, we first presented subjects with a sentence written on paper and asked them to read silently and to indicate the first meaning they perceived. Then subjects were seated in an IAC sound attenuation chamber and were presented (binaurally through headphones) with examples of the two alternative readings of the sentence. A practice session followed in which the subjects were taught how to indicate which of the two possible meanings was perceived.[5] Responses were made on the labeled keyboard of the computer in front of the subject. Subjects had to choose one of the two meanings; there was no "I'm not sure" response allowed.

After the practice session, subjects were read instructions for the task. They were told that there was no set pattern in the stimuli. Five blocks of sentences were presented to a subject.

1. "(Pat or Kate) and Bob will come" with foot ratio changing systematically from .64 to 1.53 in 12 equal logarithmic steps, then back to .64 (26 sentences).
2. The same sentence as in 1 starting from foot ratio 1.53 and changing systematically to .64 and then back to 1.53 (26 sentences).
3. "Pat or (Kate and Bob) will come" with foot ratio changing systematically from 1.53 to .64 and back (26 sentences).

[5] We introduced the practice session because during a pilot study, when we presented the two alternatives on the screen (with a reminder of which key corresponds to which meaning), the sentence that the subject happened to be looking at influenced interpretation of the sentence heard over the headphones. Thus we had subjects memorize which key corresponds to which interpretation and got rid of the visual presentation of the alternative meanings.

4. The same sentence as in 3, starting from foot ratio .64, changing to 1.53 then back to .64 (26 sentences).
5. A set of randomly ordered sentences.

The order of the blocks was the same for each subject.

Before every sequence, subjects were told the meaning of the first sentence and what their response should be. This was done to ensure that the subjects began with the appropriate initial bias. For the remaining 25 sentences in each block, they were asked to judge the meaning by themselves. Subjects had 4 s to make a response, but they were asked to make their responses as soon as possible. Response times were not recorded in this first experiment. After completing the four sequences, there was a short break and then the random condition was presented (70 sentences). The entire experiment took approximately 1 hr.

Subjects

Ten subjects participated in the experiment. The data of one subject were discarded because the subject failed to produce only one response per stimulus sentence. The remaining nine subjects were female, undergraduate psychology students who received credit in their introductory psychology course for participating. Subjects had no known hearing disorders.

Results and Discussion

For each subject we first analyzed data from the random condition. The percent of sentences identified as meaning (PK)B was plotted as a function of foot ratio. Obtaining a typical identification function indicates that altered foot ratio was sufficient information for categorizing sentences as conveying one meaning or the other. Of nine subjects, five showed fairly typical identification functions (see Fig. 1) (data from the very end of the continua were sometimes distorted, which can be attributed to the extreme manipulations being perceived as unnatural), three subjects showed identification functions that were somewhat "flatter" (i.e., the extreme examples classified with around 30/70% instead of 0/100%), and one subject performed at chance level. In what follows, we focus on those subjects who showed typical identification functions, because only in these cases we can be sure that foot ratio had provided sufficient information for categorization. For the other four subjects, the cues that were left in the sentence (e.g., naturally varying fundamental frequency) may have overridden the influence of foot ratio. That individuals gave different weights to the many acoustic cues present in the signal is not without precedence (e.g., Bell-Berti, Raphael, Pisoni, & Sawusch, 1979).

Each subject's performance on each sequence of sentences was investigated separately. The patterns of responses are shown in Table II. We considered the type of patterns of responses generated by subjects and the similarity between patterns, and considered if those patterns might support the view that the process of categorization has two relatively stable states with a region of bistability in between.

The predominant pattern of responses was hysteresis, as can be seen in Table II. Hysteresis in this situation means that a given interpretation of a sentence tended to persist before switching, even though the value of the foot ratio parameter favored the alternative interpretation (as seen in the identification function computed from the random condition); (Fig. 2, top). In the remaining runs we observed enhanced contrast (the subject switched at the earlier parameter value on the way back; Fig. 2, middle), and critical boundary (the subjects switched at the same parameter value in both parts of the run; Fig. 2, bottom). Hysteresis was observed on 13 of 20 runs, enhanced contrast on 6 runs, and critical boundary (which would be the correct place to switch if the value of the parameter was the only factor determining the categorization) occurred only once. Thus the same stimuli were perceived differently in the first half of the sequence than in the second half.

Although the sequentially ordered stimuli allow for stronger contextual influence of previous percepts, weaker contextual influences should also be manifested in the random condition. Thus for the random condition we calculated the conditional probabilities of perceiving one sentence meaning a) when the meaning of the immediately preceding stimulus was perceived as being the same, and b) when the immediately preceding stimulus was perceived as the alternative meaning. We found that the probability of perceiving a given meaning was higher when the subject heard the same meaning immediately before and was lower when a different meaning was perceived before. In Fig. 4 we present the conditional probabilities data

Table II. Preferences and Patterns of Responses in Sequential Presentation Condition

		Response pattern			
Subject	Preference	Block 1	Block 2	Block 3	Block 4
JC	B	Hysteresis	Hysteresis	Enhanced contrast	Hysteresis
LB	B	Hysteresis	Hysteresis	Hysteresis	Hysteresis
JM	P	Enhanced contrast	Critical boundary	Hysteresis	Hysteresis
RT	B	Hysteresis	Enhanced contrast	Enhanced contrast	Enhanced contrast
TG	B	Hysteresis	Hysteresis	Hysteresis	Enhanced contrast

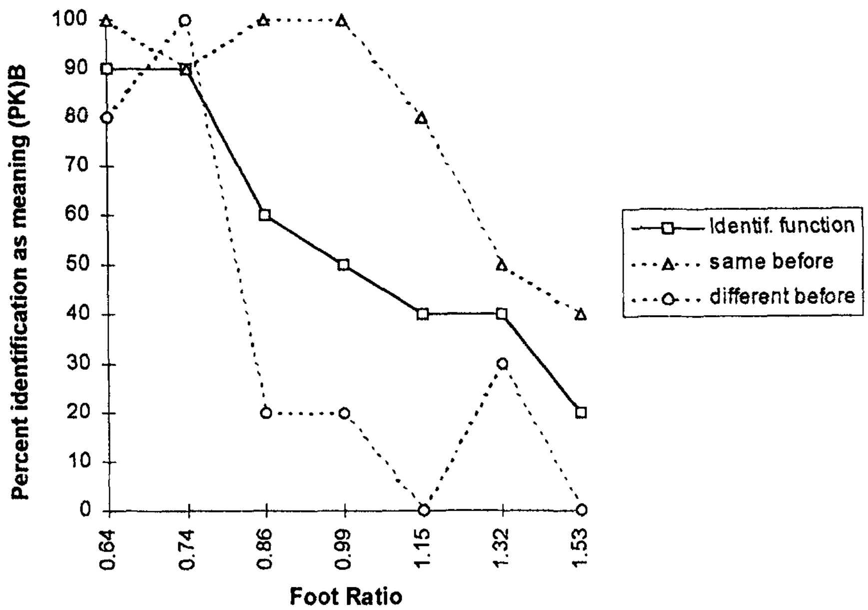

Fig. 4. Conditional probabilities computed from the random condition for subject JC. □ = identification function; △ = probability of perceiving a stimulus as (PK)B given the same percept before; ○ = probability of perceiving a stimulus as (PK)B given different [P(KB)] percept before.

from the random condition of a subject who in the sequential runs showed hysteresis (JC). The individual runs showing the hysteresis effect and conditional probabilities computed from the random condition exhibited the same characteristic pattern of response.

Results clearly indicate nonlinear dynamical characteristics for subjects for whom foot ratio was a sufficient variable to disambiguate sentences. The presence of hysteresis indicates the coexistence of two possible interpretations for identical sentences and the dependence of a system on its recent history. The hysteresis region allows us to look at the categorization process as a transition in a multistable system. Starting from having only one state (category) available, the manipulation of a control parameter (relative foot duration) drives the system into a ***bistable region,*** in which a new meaning becomes available. At some critical parameter value the first meaning probably loses stability, leaving only the new one available. In the bistable region, which of the two responses will actually be observed is dependent on the previous context. This property provides a viable explanation for flexibility of categorization in various contexts (because more than one pattern is available). Thus it might be that the global perception of sentence meaning can be due to similar underlying dynamics that has been uncovered in perception of other stimuli (see, for example, Kelso et al., 1995), establishing the notions of dynamics in the psycholinguistic realm. Following the work of Tuller et al. (1994), such behavior can be modeled as an equation describing the evolution of a collective variable, reflecting stability of the percept as a function of the control parameter.

A THEORETICAL MODEL

A brief outline of a model that captures the patterns of responses obtained will follow (for a more detailed description see Tuller et al., 1994; for a more general introduction to applications of dynamical systems theory to biological systems see Kelso, Ding, & Schöner, 1992).

The underlying dynamics of a perceptual situation presented above—capable of displaying the phenomenon of hysteresis—can be captured by a simple two-well potential function:

$$V(x) = kx - x^2/2 - x^4/4 \tag{1}$$

where x is the sentence interpretation and k is the control parameter (in our case, scaled foot ratio). In this equation k specifies the direction and degree of tilt for the potential $V(x)$. The potential function is derived from the equation of motion:

$$dx/dt = -dV(x)/dx \tag{2}$$

Thus the minima in the potential function correspond to fixed points in the dynamics of x. Figure 5 shows the shape of $V(x)$ for several values of k (values of k are chosen to illustrate the qualitative behavior of the system; the exact quantities do not matter here). For $k = -1$, only one stable fixed point exists, corresponding to one meaning of the sentence. Such a situation remains as k increases (i.e., foot ratio increases), although the potential landscape tilts so the minimum becomes more shallow, up to the point when it reaches critical value ($-k_c$). At this point a bifurcation in the system occurs (a saddle-node bifurcation) and an additional attractor appears. This new attractor corresponds to the alternative interpretation of a sentence. Notice, however, that when the value of k_c is approached systematically, the system (which can be imagined as a ball in this landscape) will remain in the initial minimum (i.e., will maintain the initially perceived sentence meaning). Only when a further deformation of the potential occurs, at which the attractor corresponding to the first interpretation ceases to exist (via a

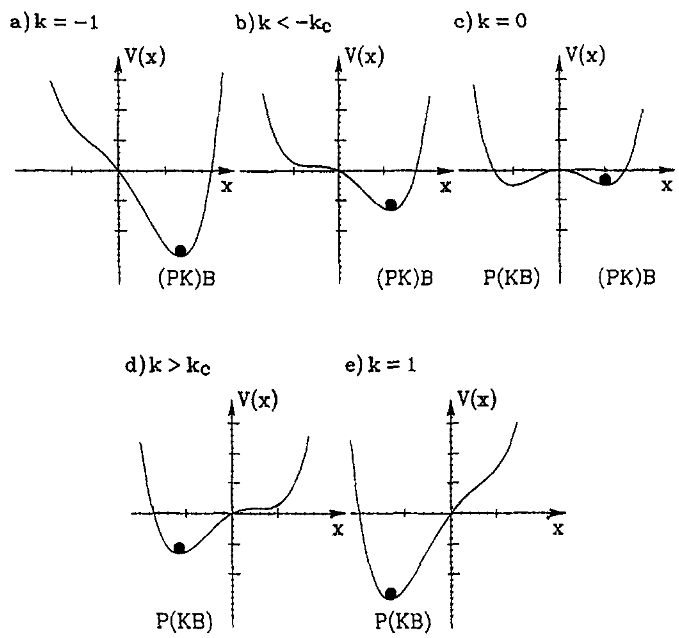

Fig. 5. The shape of the potential function for five values of the parameter k (see text).

reversed saddle-node bifurcation), will the perception switch to the new attractor. Thus, in the region from k_c to the value of k when the initial stable fixed point disappears, we have a region of parameter values for which two stable points coexist (bistability), and the history of the system (i.e., from what values of k the system approaches this region) decides which alternative will be perceived.

Further development of the model should include the ability to account for the influence of preference on the dynamics, possibly in the form of additional *initial* asymmetry in the model. From our experiment we know very little about this, since only one subject with a typical identification function had a preference for meaning P(KB) of the investigated sentence.

As it is, the model can account for the hysteresis (by far the most prevalent pattern obtained in the experiment) and critical boundary patterns. The model can be extended to include enhanced contrast pattern, as demonstrated in the work of Tuller et al. (1994), by recognizing that perhaps the effects of learning or attention may alter the rate of change of the potential tilt. Possibly the nature of the stimuli we used in our study and the design were responsible for the predominance of hysteresis. In Tuller et al., subjects listened to a much greater number of simpler stimuli, and the pattern of enhanced contrast was more frequent (for a detailed account of the factors influencing probability of the two response patterns see Tuller et al., 1994).

One possible objection to our interpretation of the data is that subjects may not have been listening to the entire sentence but focused only on local cues to give their interpretation. Especially with training on the stimuli that are the extreme examples of alternative meanings, the listener may not respond on the basis of the global pattern, but instead respond on the basis of whether the individual word "Pat" or "Bob" is most similar to the same word in the "good" exemplar. Thus subjects could have learned to respond using a strategy of focusing on some particular cue, for example, the length of the vowel in "Pat" and then ignore the remainder of the sentence. Although categorization still occurred, can we really claim that it was the categorization of global sentence meaning?

Experiment 2 had two main goals: one was to address the above-mentioned issue, the other was to explore the patterns of response times obtained in the regions of stable percepts and in the regions of putative instability. We reasoned that if switching of the interpretation can be seen as a transition between two stable patterns, then the stability of these patterns should differ depending on how far the system is from the transition. Since a transition in dynamical systems is postulated to be brought about by the previous percept losing stability, it should be preceded by the minimum getting shallower (the state getting less and less stable). If a minimum is shallow, it takes longer for a system to settle in it (so called "critical slowing down" before the transition). Based on an assumption that recognizing a meaning is equivalent to settling into a stable pattern, the closest estimate of the "time to settle down" we have in a linguistic task is the time of deciding which meaning a subject hears. It should therefore take longer to decide which meaning is conveyed by a sentence as a transition to the alternative meaning is approached.

EXPERIMENT 2

Materials

Stimuli included a subset of those used in experiment 1. Continua were shortened such that the sentences with the foot ratio most changed toward the alternative interpretation were removed (i.e., the last manipulated sentence of initial production (PK)B had foot ratio 1.42 and the most altered version of meaning P(KB) had foot ratio 0.69). Moreover, at the ends of the continua we presented stimuli with larger step changes in foot ratio, i.e., every second sentence (to make the task less tiresome), but presented all stimuli with intermediate parameter values (seven sentences). Thus each continuum consisted of 18 stimuli (nine sentences presented with foot ratio increasing then decreasing or foot ratio decreasing and then increasing).

All the sentences used were digitized using the ILS package. Sentences were recorded on a single channel and on the second channel a 1000-Hz tone was recorded at the beginning of each sentence. All sentences, together with the tones, were then recorded on a Marantz stereo tape recorder, which was also used to present the sentences to the subjects. The tone, which was inaudible to the subject, triggered a Uher dia-pilot, connected to a Dell computer and started a timer. The timer stopped when the subject responded or 2 s after the sentence finished, whichever came first.

Procedure

As in experiment 1, subjects' initial preferences for sentence meaning were collected. We then presented four sequences of sentences (18 sentences each) and two blocks of 90 randomized sentences. The order of presentation was the same for each subject. The rest of the procedure was the same as that for experiment 1. Subjects were asked to press a key on the response pad in front of them after each sentence as soon as they decided which meaning they heard. It was emphasized in the instructions that the subjects should make their answers as soon as possible.

Subjects

Sixteen students of Florida Atlantic University participated in the experiment: 13 undergraduate and 3 graduate; 14 female, 2 male. Undergraduate students received credit in their Introductory Psychology class for participation.

Results and Discussion

Ten of the 16 subjects demonstrated typical identification functions and only data of these subjects were included in further analyses. Again, the main pattern observed with sequential changes in foot ratio was hysteresis. Of the 40 data series, 26 showed hysteresis, seven showed critical boundary, six enhanced contrast, and one subject did not experience transition in the perceived meaning on one sequential run. Similar conditional probability patterns were observed for the random presentation, i.e., usually the probability of perceiving a given meaning was higher after perceiving the same meaning before than after perceiving a different meaning. It is interesting to note, however, that four of six enhanced contrast patterns an two critical boundary patterns were accounted for by only two subjects. An examination of the pattern of conditional probability for these subjects showed that also in the random condition the previous percept did not make the subjects "stick" to the perceived interpretation. In Fig. 6 a comparison of performance in the random condition between two subjects is presented. Figure 6a depicts conditional probabilities for a subject who showed only hysteresis, and Fig. 6b those for a subject who showed predominantly enhanced contrast on sequential runs. It appears that the strength of the tendency to stay in one meaning is specific to a subject and varies interindividually. In previous research, it was demonstrated that the rate of spontaneous ambiguous figure reversals (which is also a type of pattern switching) was correlated with cognitive flexibility, itself a characteristic of the cognitive style of a person. Therefore our result is congruent with earlier suggestions that people vary on the dimension of pattern seeking; the fact that we did not see a uniform pattern (e.g., hysteresis) on individual runs may be due to this factor.

The average response time from the beginning of the sentence was 2502 ms (*SD* 609 ms). Even though there was considerable variability, subjects appeared to respond only after at least the phrase containing 2 feet (1400 ms) was presented (see Fig. 3). Most often subjects responded after the whole sentence (2300 ms). One subject reported listening to the "part with names" and two subjects reported that they used "pauses after both

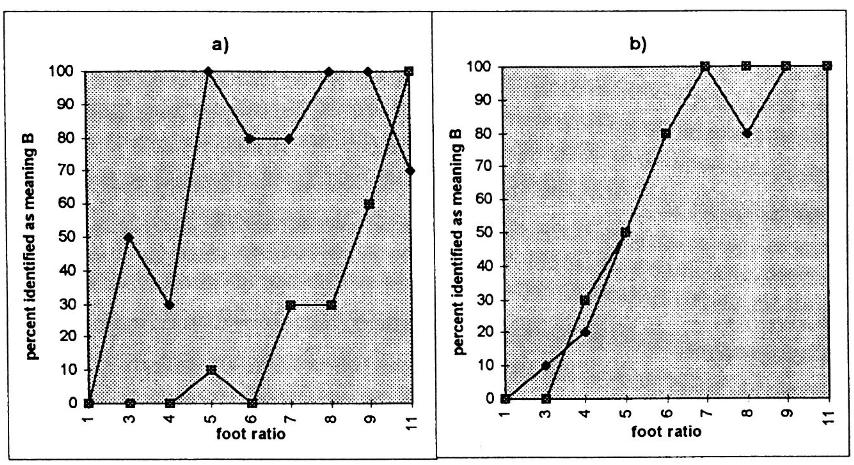

Fig. 6. Conditional probabilities in random presentation condition for two subjects with different tendency to switch: (a) for a subject who displayed hysteresis on all four sequential runs, (b) for a subject who displayed two enhanced contrast patterns, one critical boundary, and one hysteresis. ◆ = probability of perceiving a stimulus as (PK)B given the same percept before; ■ = probability of perceiving a stimulus as (PK)B given different [P(KB)] percept before.

names" as cues for distinguishing the meanings. Other subjects could not clearly indicate their strategy. Thus our first consideration—that subjects might have focused on a single cue (e.g., vowel duration in 'Pat')—although not completely ruled out, seems unlikely given the long response times despite instructions to respond as quickly as possible.

The second reason for gathering response time data was to observe their characteristics in theoretically stable and unstable regions. We expected longer times in the unstable regions since it takes longer for a system to settle down in a shallow minimum than in a deeper one. Results confirmed our expectations. An example of the pattern of response times from a single subject on a single run is shown in Fig. 7.

Of course, not all patterns obtained were as clear as this one, but they had similar characteristics. We compared the response times close to the perceptual transitions with response times further away from transitions by considering three responses before each transition and three after. The last responses before transition should be longer than those two or three steps away from the transition. In other words, we compared response times for foot ratio parameter values where the percept was theoretically stable with those where the percept was close to switching to the alternative sentence meaning. The means and mean standard deviations at each step are shown in Fig. 8.

A one-way repeated measures analysis of variance with six levels of distance from the transition (i.e., three, two, and one step before, and one, two, and three steps after the transition) showed a significant effect, F (5, 250) = 9.7, $p < 0.0001$. Further analyses revealed significant contrasts between the third step before the transition and the second, F (1, 50) = 8.50, $p < 0.006$, the first, F (1, 50) = 28.27, $p < 0.0001$, and the first after the

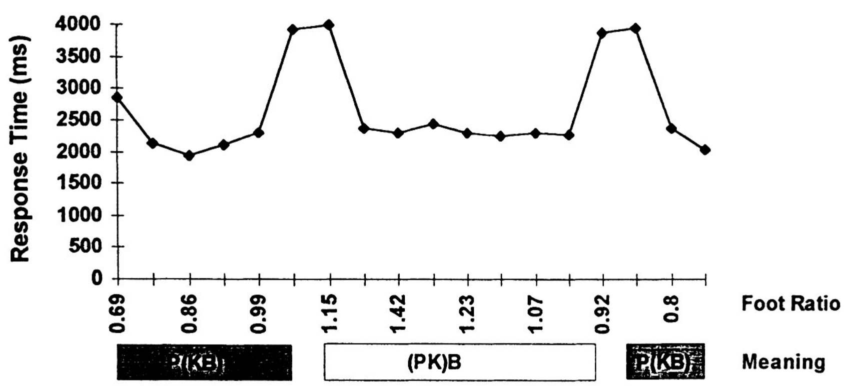

Fig. 7. Example of the pattern of response times obtained from a single run of a single subject. P(KB) and (PK)B are the two alternative meanings.

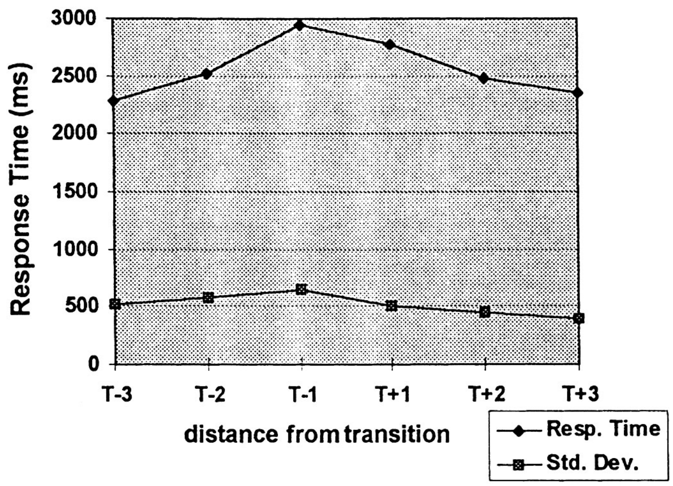

Fig. 8. Response times and standard deviations near transition. T−3, T−2, T−1 denote third, second and first step before the transition; T+1, T+2, T+3 denote first, second, and third step after transition, respectively.

transition, F (1, 50) = 9.20, $p < 0.004$. The pattern of response times after the transition also confirmed our expectations: The first step after the transition was significantly slower than the second step after the transition, F (1, 50) = 10.29, $p < 0.002$, and the third step after the transition, F (1, 50) = 14.24, $p < 0.001$.

We also compared response times for the last identification of a given meaning to the response times obtained at the first response after switch. According to our explanation, the response times after a switch should decrease because the percept should already have some stability. The difference between the means obtained was in the predicted direction: 2778 ms right before switching vs. 2574 ms right after switching, F (1, 50) = 3.34, $p < 0.07$.

Summarizing the results of experiment 2, we can conclude that: (1) responses as to which meaning was presented were most likely made after listening to the pattern of timing in at least two feet, and (2) near the transition points the response times were longer than in the regions far from the transition, and response times right before the transition were slightly longer than right after the switch. Both of these outcomes are consistent with the idea of a "dynamics of meaning." The longer response times near transitions are suggestive of loss of stability from which eventually a transition to an alternative meaning results. Again, it is important to note that it was not the value of the foot ratio alone that determined the response times. Rather, the recent history of the system, that is, the previously perceived meaning, had a considerable effect. Thus for two presentations of identical sentences, we obtained systematically different response times, which suggests that sentences with the same foot ratio are characterized by different stability depending on the recent history of the perceptual system. Finally, individuals seem to be internally consistent and at the same time differ among one another with regard to the "readiness to switch," a variable associated in previous studies with cognitive flexibility.

GENERAL DISCUSSION

The most important outcome of these experiments is the fact that a sentence that has one meaning in isolation may be biased toward another meaning by the ordering of a relevant acoustic cue across *prior* stimuli. Due to: (1) the presence of hysteresis as the predominant pattern in the sequential condition (Fig. 2 top), (2) the values of the conditional probabilities in the random condition (Fig. 4), and (3) the dependence of response times on sequential context (not only foot ratio) (Fig. 7), we can treat the change in the perceived meaning of a sentence as a transition between relatively stable regions of order parameter dynamics. Driven by a control parameter (relative foot duration), perception moves from one stable meaning into a bistable region, and finally, with further modification of the control parameter the old stable meaning is lost and only the alternative meaning remains available.

Characterizing states corresponding to alternative meanings in terms of stability has several important consequences. Once the growing instability leads to a change in the sentence's perceived meaning, the emergence of a new pattern induces "enslaving" of the rest of the cues (e.g., fundamental frequency contour or amplitude) so as to form a coherent alternative organization, i.e., another stable state. It is the existence of this coherence that allows for a low-dimensional description of this process in the form of a differential equation, where sentences (coherent patterns) are treated as attractive regions of the dynamics (see, e.g., Tuller et al., 1994). The equations of motion for the system's collective behavior (the alternative meanings) can capture the temporal evolution of this self-organized pattern formation process (its instabilities, bifurcations, etc.). Such a theoretical model allows for new predictions, for example, prediction of the relative response times as a function of stability (as shown in experiment 2) and of the differential effect of noise (perturbations) at different values of the control parameter (see Tuller et al., 1994; Case, Tuller, Ding & Kelso, 1995). The model can also be extended to include such influences as experience with the stimuli and attentional factors (e.g., Ditzinger & Haken, 1989; Haken, 1990). In the case of sentence understanding, it would be especially useful to include the effect of preference (which meaning the subject preferred in a spontaneous reading), which will be the next step in this project.

This study demonstrated the usefulness of the concept of coherence and stability of the global pattern of a sentence for the study of sentence understanding. It did not address issues pertaining to on-line processing of particular local cues in the sentence. Rather, we showed that global effects organize local cues into a coherent percept and that off-line decisions about sentence meaning are influenced by the previous percept. We do not know whether the on-line processes involved in sentence understanding are influenced by this global organization or are informationally encapsulated. What we observed is that the local manipulation (of foot duration) changed the global interpretation, which in turn was able to influence the global interpretation of the next presented sentence. Whether the change in perception of the next sentence was effected through the change of perception of local cues or rather through influencing the integration processes remains to be seen. What we do know, however, is that even if the local cues were perceived as favoring an alternative interpretation, the global pattern of a previously perceived meaning persisted and was able to change the effect of these cues on the ultimate interpretation.

Finally, our studies contain an important message concerning the generality of processes involved in language understanding. A body of research on perception uncovered similar dynamical characteristics for stimuli differing vastly both in complexity and in modality. Recent evidence includes perception of syllables, pitch change of pairs of complex tones, orientation of apparent motion stimuli, and visual structure in Glass patterns (Tuller et al., 1994; Hock et al., 1993; Kelso et al., 1995). The presence of the same dynamical effects at the level of global sentence meaning suggests that the principles underlying the pattern formation process could be the same regardless of the level of complexity of the stimuli that are chosen for study (Kelso, 1995). What this means for language processing is that the perceptual processes involved in global sentence understanding may be of a more general nature than previously thought.

CONCLUSIONS

The dynamical approach is a promising way to look at very complex processes—here, the understanding of sentences. It encourages looking for discontinuities, sudden, nonlinear changes in perception and behavior, as revealing the underlying processes. Such an approach is becoming increasingly popular in cognition (Kelso et al., 1994), including learning (Schöner, Zanone, & Kelso, 1992; Zanone & Kelso, 1992) and attentional processes (Ditzinger & Haken, 1990; Tuller et al., 1994), and in linguistics as demonstrated by Petitot's (1994) work, which utilizes and further develops Thom's (1975) catastrophe theory in the search for new frameworks for understanding off-line language processing.

The conceptualization of sentences as having an inherent stability is congruent with early Gestalt theories (e.g., Köhler, 1940). Compare, for example, the explanations of the perception of ambiguous figures, like the Necker cube (Necker, 1832) or duck/rabbit figure, which are based on the assumption that the perceived figure has an internal organization or coherence, with our approach, which also emphasizes the search for natural principles of autonomous order formation and their importance at all levels of cognition.

Experimental verification of the dynamical properties of perception at the level of complex linguistic stimuli is valuable also from the point of view of validating models that—especially in the case of explanations of higher cognitive functions—use the notions of energy minimum and attractor without attention to experimental consequences and do not take advantage of predictions that may stem from such a conceptualization.

The notion of temporal stability of perception of linguistic stimuli allows us to study changes of this stability under various modifications and perturbations. This may aid in mapping a space of effective factors (control parameters) contributing to sentence understanding. The concept of stability takes away the burden of unequivocally specifying the values of these factors that are crucial for the change of perceived meaning: they will be different in different regions, depending on the global coherence (stability) of the pattern in a given region of this space. The important theoretical implication of this point concerns the change of emphasis in description of factors influencing categorization. The characteristics of stimuli themselves and the absolute values of these characteristics are unlikely to unequivocally determine which of the possible interpretations will be received. Thus, searching for invariant essences or intensions of categories may prove to be a futile task, at least when usual, off-line methods are employed. Instead, we might need to direct our attention to the organizational laws pertaining to the perceiving agent. It is in the perceiver–environment relation that stability of percepts can be assessed, so perhaps more emphasis should be directed toward studying phenomenological patterns and, even more importantly, their discontinuities as informative windows into the processes underlying cognition.

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