11

Information-Processing Theory and Strong Inference: A Paradigm for Psychological Inquiry

Dominic W. Massaro
University of California, Santa Cruz

INTRODUCTION

Metatheory and research strategy are inseparable components of a paradigm of psychological science. The defensive half of the present essay begins with a defense of information-processing theory and a strong inference research strategy in psychological inquiry. The basic assumptions of this paradigm are described and briefly illustrated. Previous criticisms and alternatives are evaluated and found either lacking or restatements of the same paradigm. The offensive half of the essay illustrates the usefulness of the paradigm in the study of speech perception.

A series of tests addresses important issues in the evaluation and integration of auditory and visual sources of information in speech perception by eye and ear. Sources of information refer to the features or attributes of the environment that are utilized in perception and action. Questions include (1) whether there are both auditory and visual sources of information or just a single source, (2) whether or not the two sources are integrated, (3) the continuous versus categorical nature of the information from each source, (4) whether or not the sources are independent, and (5) the nature of the rule used to integrate the sources. Definite answers to these questions illustrate the value of the paradigm in psychological inquiry.

INFORMATION-PROCESSING THEORY

In information-processing theory, the individual is viewed as a processor of information (Broadbent, 1958, 1971; Massaro, 1975a; Neisser, 1967). It should be stated that the information-processing theory is a metatheoretical framework and is much more general than any particular methodology such as the additive-factor method (Sternberg, 1969). The researcher attempts to understand what happens to the information as it is perceived, interpreted, and acted upon by the individual. The processing of environmental information depends on the nature of the relevant sensory systems, some memory of past experiences, the relevant motor systems, and goals of the participant.

One central assumption of research within the information-processing paradigm is that observed performance in some domain involves a sequence of processing stages. The onsets of these processing stages are successive and each stage operates on the information available to it. The operations of a particular stage take time and transform the information available to it. The transformed information is made available to the next stage of processing. Two theoretical constructs are important in this approach. First, the memory construct describes or defines the nature of the information at a particular stage of processing. Second, the processing construct describes the operations performed by a stage of information processing. The information-processing paradigm provides a framework that can be implemented using a variety of experimental methods, manipulations, and dependent variables. Examples include the additive-factor method and backward recognition masking.

The information-processing approach has major implications for research. It is necessary to account for each of the processing stages in a task performed by individuals. This requires that the investigator make explicit the implicit assumptions inherent in the experimental situation. Failure to do so severely limits what can be learned from the results. The precise analysis given by the information-processing methodology can be thought of as a microscope. It allows the experimenter to see what is not directly observable. As an example, the additive-factor methodology has been reasonably successful in providing glimpses at recognition, memory search, and response selection processes (Massaro, 1984c; Sanders, 1980; Sternberg, 1975; Theios, 1975)

Limitations of Current Information-Processing Models

A prototypical information-processing model aims to specify (1) the time course of mental operations, (2) the nature of mental operations, and (3) the nature of memory structures that hold information. In contrast to what might be expected from their name, information-processing models have not really been all that concerned with information. Information is taken to mean the actual aspects of the environment that are informative. Noting the failure of an earlier enterprise, unidimensional information measurement in explaining psychological phenomena, Neisser (1967) helped shape the view of information in the information-processing model: "Information is what is transformed and the structured pattern of its transformations is what we want to understand" (pg. 8). This statement seemed to give license to relegating information to a minor role in information processing.

Within the information-processing framework, many researchers sought to define the time course and nature of mental operations without really specifying the nature of the information used in particular domains. These researchers used rather arbitrary stimuli (tones, lights, letters, words) without really being concerned with their function in the real world. The implicit assumption was that the time course and nature of mental operations could be defined independently of the nature of the stimuli being processed. Although this research was a profitable enterprise, one obvious legacy was a model in search of a natural domain to describe.

The limitations of pure information processing became apparent to this writer when I and a group of students applied the model to language processing (Massaro, 1975b). Consistent with the information-processing approach, many facets of understanding language were illuminated by accounting for the stages of processing involved. For example, isolating the perceptual unit functional in speech perception required analyzing the memory structures and psychological processes involved in the task of perception. What became obvious, however, was that the language information was as important or more important than the processing of that information. A complete theory had to describe not only what is done with information but also what is used as information.

Consider the role of time. The time available for processing information is important in speech perception as it is in domains with simple artificial signals (Massaro, 1975b). However, time also is information in speech in that some speech distinctions such as vowel identity and consonant voicing are cued by the duration of the speech segments (Massaro, 1984b). Thus, the potential information in the language signal and its utilization by the language user had to be described as well as the time course of perception, decision, and memory. The information-processing paradigm was still the best game in town because it provided a coherent framework for the finding of analogous processes in speech perception and reading (Massaro, 1975b, 1978, 1979).

Alternatives to Information-Processing

Some of the opposition to the information-processing paradigm proposed that there should be a concern for natural environments. Theorists within the Gibsonian framework ask that investigators focus on the higher order structure of the environment and relate it to behavior (Gibson, 1979; Huber, 1983; Turvey, 1977; Turvey & Shaw, 1979). The implicit assumption in this proposal is that there are complex environmental invariants responsible for much of behavior and the goal is to discover these properties to explicate behavioral observations. Studying behavior in a natural situation follows naturally given this assumption. If these higher order invariants are eliminated as supposedly occurs in simple laboratory tasks, then they cannot be discovered. Thus, we see that the non-Gibsonians are concerned with one traditional problem in scientific inquiry called external validity or the degree to which one can generalize from the experimental to the natural situation.

The Gibsonian framework is similar in many important respects to the classical psychophysical approach inaugurated by Fechner (1860), in which variation in the stimulus world is related to variation in performance. Both Fechnerian and Gibsonian paradigms dictate the discovery of relationships between objective and subjective worlds without fundamental concern for the intervening mental processes and representations. In contrast to the Titchenerian assumption of the whole being composed of component parts, however, the non-Gibsonians, like the Gestaltists, believe that higher order invariants are directly perceived and will stand on the left side of the S–R chain. Both the component-cues and higher order invariants proposals bring the investigator into the domain of psychophysics.

These two approaches to the study of the world of information have produced somewhat disappointing results. Gibson and the non-Gibsonians have not yet delivered with respect to discovering higher order invariants (see Shebilske and von Hofsten chapters, this volume). Looking out my window at grass, weeds, and trees, there is no apparent single higher order invariant that can capture my experience of depth and object constancy. The knowledge acquired in the psychophysical study of component cues has also been relatively limited (Rock, 1975). Although many cues have been proposed, very little insight has been gained into how the perceiver evaluates and utilizes the cues in perception. We have not learned the relative importance of the cues nor how the multiple cues work together. (A recent study by Cutting and Millard (1984) has, at least, begun to address the relative importance issue.) As we will see, one limitation in the traditional psychophysical approach has been the experimental design of asking how one cue works when other cues are neutralized or held constant. The single-cue paradigm not only fails to define how the particular cue would operate in a more natural situation, it also does not address the issue of how the perceiver evaluates and integrates multiple cues in perceptual processing.

INTEGRATING INFORMATION AND INFORMATION PROCESSING

My goal in this essay is to integrate the information-processing approach with the study of the world of information. The paradigm that makes this resolution possible can be attributed, in part, to Egon Brunswik (1952, 1955, 1956), who anticipated some of the trends currently in vogue in psychology. In contrast to Helmholtz's (1962) idea of perception guided by unconscious logic, he viewed perception as a primitive and autonomous process. This view subsumes Fodor's

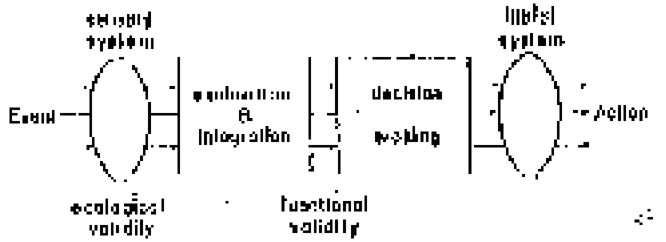

FIG. 11.1 Schematic diagram of the Lens model of Brunswik, illustrated in a more contemporary format. Ecological validity refers to the aspects of the physical and sensory world that are informative about some object or event. Functional validity refers to those aspects that are actually utilized by the observer in perception and action.

(1983) thesis of separate and autonomous modules for different psychological functions such as visual perception and language. Brunswik also called for the study of natural situation rather than artificial experimental tasks. Thus, calls to natural ecology in the study of perception such as those by Neisser (1976) and Haber (1983) were already existent in the psychological literature decades earlier. Brunswik also acknowledged multiple but ambiguous sources of influence on behavior. Brunswik proposed the concept of probabilistic functionalism based on the idea that there are many cues determining behavior. However, the cues were seen as equivocal and only probabilistically related to behavior. Brunswik (1955) stressed "the limited ecological validity or trustworthiness of cues. . . . To improve its (the organism's) bet, it must accumulate and combine cues" (p. 207).

Integrating multiple sources of information appears to be a natural human function. It appears to persist regardless of the intentions (goals and motivations) of the perceiver. Consider an early experiment carried out by Brunswik (described by Tolman, 1956). Subjects were asked to equate groups of coins that varied in number, area, and monetary value. Even though subjects were instructed to use just one of these three dimensions, their judgments were significantly influenced by the irrelevant dimensions.

One consistent generality in perception and cognition is the person's inability to selectively process only some aspect of the given environment. This principle is best illustrated in the Stroop color-word task. Subjects cannot ignore the name of a word when they intend to name the color of the word's type. Consider a similar effect in person impression. Subjects given a list of adjectives are asked to rate the person described by these adjectives and then to rate only one of the adjectives. The rating of the single adjective is influenced by the other adjectives in the list. This is called a positive context effect, because the likeableness value given the single adjective will be biased towards the values of the other adjectives in the list.

Brunswik is best known for his lens model, illustrated in Fig. 11.1 within a more contemporary format. With respect to the world of information, Brunswik distinguished between two kinds of validity. Ecological validity defines what cues are informative about the structure of the world. As an example, height in the vertical plane can be shown to be correlated with distance of the object from the observer. Functional validity defines what cues people actually use in perceptual processing. Given this distinction, it can be seen that a concern for ecological validity is not sufficient, because some ecologically valid property of the physical world may not be used and hence not be functionally valid. One might expect that functionally valid cues might always be ecologically valid, but many counterexamples exist. The gambler's fallacy of using the outcome of a preceding roll of the dice to guide prediction of the current roll is one of many ecologically invalid decision heuristics. A complete description of the environmental-behavior relationship requires an analysis of both ecological and functional validity.

Representative Designs

Complementing the theoretical notions of probabilistic functionalism, Brunswik (1955) proposed a unique methodological framework for psychological study. The framework called for representative designs or designs that are random samples of natural ecology. Thus, only correlational rather than experimental methods could be used because behavior must be studied within the context of the multiple cues as they co-occur in the natural world of the observer. In this regard, Brunswik anticipated Neisser's (1976) call to natural ecology by a few decades. Brunswik argued that single-factor and factorial designs are artificial because they decorrelate naturally occurring cues. For this reason, Brunswik contended that experimental results cannot be generalized to the real world. He made a distinction between internal and external validity. The results derived from a factorial design may be internally valid but yet may not be externally valid because they have no generality outside the experiment itself.

Brunswik's concept of representative design is nicely illustrated in a study of size constancy (Brunswik, 1944). The subject was asked to estimate the size of various objects in a natural setting across a wide range of sizes and distances. The subject judged the size of trees, telephone poles, bookcases, inkwells, and so on. The primary measure of performance was a correlation between the subjective estimates and objective physical size. In other studies, Brunswik and Kamiya (1953) found some ecological validity for the proximity of two lines as a cue to those lines defining the boundaries of a single object. Similarly, Seidner (Brunswik, 1956) found that vertical position of points was positively correlated with distance from the observer. It should be noted, however, that these latter two observations were only demonstrations of ecological validity because they did not evaluate functional validity in terms of the extent to which these cues are utilized in perception and recognition.

The finding of only moderate ecological validity for various cues probably contributed to Brunswik's development of probabilistic functionalism, meaning that objects and goals in the environment are only probabilistically related to the available cues. A cue such as height in the vertical plane is an equivocal, and thus a probabilistic cue to depth in that it only predicts depth with some probability. Having been informed by the development of fuzzy sets (Zadeh, 1965) and continuous information (Massaro & Cohen, 1983a), however, we see that an equivocal cue might be better thought of as providing fuzzy rather than probabilistic information; that is, a depth cue provides continuous information about the degree to which a given depth is present.

Limitations of Representative Designs

Representative designs impose a major constraint on the type of psychological investigation that can be done. If two cues do not occur independently in the natural world, then they cannot be manipulated independently in the psychological investigations using representative designs. For this reason, representative designs are inadequate for psychological inquiry. The creation of artificial situations by utilizing factorial designs, on the other hand, can be very illuminating as I hope to demonstrate in our study of bimodal speech perception. With respect to external validity, one needs only a good theory that will allow generalization from a particular experiment to the real world even if the experiment is not representative of the real world.

Information-Integration Framework

Anderson (1981, 1982) can be viewed as an intellectual descendant of Brunswik's probabilistic functionalism, but not of representative designs. Within the framework of information integration, it is accepted that there are multiple sources of information, the goal is to define the sources of information and to assess how they are integrated in perception and decision. In contrast to Brunswik's representative design, however, information integration is studied by utilizing factorial designs that manipulate independently multiple aspects of the environment. In our study of bimodal speech perception, we combine the information-integration paradigm with the research strategy of strong inference.

RESEARCH STRATEGY

Falsification

The foundation for strong inference has been expressed most succinctly by Popper's (1959) falsification strategy in research endeavor. The central assumption is that hypothesis testing must follow deductive rather than inductive methods. Following Hume, Popper claims that we are not justified in inferring universal statements from singular ones. Any conclusion drawn inductively might always turn out to be false. Although we can generate many instances of positive results, the theory might still be exposed as false. As scientists, we should guard against simply trying to verify a particular hypothesis by demonstrating that it works in specific instances. Because new instances can always falsify a given statement, no experimental observation can verify a hypothesis. A critical feature of Popper's scientific framework is that verifiability and falsifiability do not have a symmetrical relationship. Although theories can be falsified, they cannot be truly verified.

Strong Inference

Platt's (1964) extension of Popper's framework encourages scientists to employ a strong inference strategy of testing hypotheses. In contrast to generating a single hypothesis, Platt would have the scientist generate multiple hypotheses relevant to a particular phenomenon of interest. The experimental test would be designed to eliminate (or in Popper's words, falsify) as many of these hypotheses as possible. The results of the experimentation would allow the generation of new hypotheses that could be subjected to further tests. Both Platt and Popper adhere to David Hume's axiom prohibiting inductive arguments. Given that the scientist should not attempt to confirm a single pet hypothesis, Platt's solution is more productive in that at least one of the multiple hypotheses under test should fail and can, therefore be rejected.

Criticisms of Falsification and Strong Inference

Falsification and strong inference have been criticized as scientific frameworks for psychological inquiry. In an influential paper called "You Can't Play Twenty Questions With Nature and Win: Projective Comments on the Papers of this Symposium," Newell (1973) makes two relevant points. The first point is that psychology, in its current style of operation, deals with phenomena. Clever experiments bring these phenomena into existence. As an example, by manipulating the relationship between successive lists of items to be remembered, one can demonstrate release from proactive interference or the progressive decrease in memorability with repeated learning of new lists of items. Newell's second point is that the guide to investigating these phenomena is one of construction of oppositions, usually binary ones. Thus, we test between nature versus nurture, central versus peripheral processing, or serial versus parallel processing, and so on. Newell listed both a large number of phenomena of psychology and many binary oppositions current in research, generated within the research framework of falsification and strong inference. Newell's argument is that our accumulation of phenomena and tests of binary contrasts are not really adding up to scientific progress in psychological inquiry.

Newell (1973) proposed the following solutions. First, know the method that your subject is using to perform the task. Second, never average over methods. Third, it is necessary to integrate research from a wide variety of domains. To achieve these solutions, Newell suggested that we need to develop complete processing models; analyze complete tasks; and construct a theory to perform many different tasks.

Newell's critique of strong inference is not convincing and, in fact, his dicta seem highly compatible with this research paradigm. Newell advocates exploring a complex task exhaustively, not simply in terms of the binary oppositions that can be defined for it. I am skeptical of this proposal if it represents theory-independent research, because data without theory are meaningless. The question we face is simply whether testing binary contrasts is a valuable approach to scientific investigation. The use of binary contrasts, such as in the question of the integration or nonintegration of information from different sources, appears to be fundamental to psychological inquiry. The interpretation of any experiment done with bimodal speech, for example, is critically dependent on whether or not subjects do in fact integrate the information from the multiple sources. Any theory that does not address this binary question could be wrong at a fundamental level because various results could be interpreted in terms of an integration process even though integration did not occur (Anderson & Cuneo, 1978).

Jenkins (1980) has also been critical of research carried out at an elementaristic or atomistic level based on the assumption of "bottom-up" inquiry. The goal within this paradigm is to find the basic laws of elementary processes with the belief that combinations of these basic laws will be sufficient to account for complex situations. Jenkins (1980) believes that this research enterprise is doomed to failure because it is "*relations* among elements that count rather than just the elements alone" (p. 223). As Jenkins (1979) has nicely illustrated, any generalizations about memory will have to include interactions with the nature of the subjects, the orienting tasks, the criterial tasks, and the materials. There are not simple one-dimensional rules of memory. As a solution, Jenkins (1980) proposes a research enterprise involving the close interaction between experiment and model building or analysis and synthesis, a solution highly compatible with the paradigm defended in this chapter.

In a review of progress in memory research, Tulving (1979) acknowledged the explosion of research and theory but remarked that "it is not clear that we know what all these facts and findings mean or what they add up to" (p. 27). Tulving believes that the science of memory has not yet obtained its first genuine Kuhnian (1970) paradigm. Until it does, Tulving offers the following advice. Don't spend too much time affirming what we already know, explaining the commonsensical, accounting for results of single experiments, and developing quantitative theories when the basic concepts are still lacking. These caveats by Tulving seem to have little substance. I agree that we should not simply affirm what we already know but we should test among alternative explanations of the facts. With respect to Tulving's advice against explaining the commonsensical, it may be the case that what on the surface seems commonsensical is actually the consequence of a set of interacting unintuitive processes. Accounting for the results of a single experiment is usually necessary to develop hypotheses to be tested in subsequent experiments. Finally, developing quantitative theories often leads to the discovery of basic questions and concepts.

Although Newell, Jenkins, Tulving, and others (e.g., Allport, 1980; Gopher & Sanders, 1984; Sanders, 1984; Stelmach & Hughes, 1984) have provided valuable reflections on aspects of research strategy, their advice does not seem to warrant rejection of the "information-processing" and "strong inference" paradigm. I believe that the best way to achieve Newell's goal of exhaustive analysis of a complex task is via information-processing theory and strong inference research strategy. If it is the relations among the elements that count, as Jenkins argues, one has to first understand what the elements are and only then how they relate. Building models requires the utilization of elementary processes and hypotheses about how these processes are organized to account for complex behavior. We are in complete agreement with Tulving's last piece of advice to be skeptical of intuitive and transparent theories and follow the precepts of "strong inference" (Platt, 1964).

One of the persisting criticisms of the information-processing approach is the failure to give satisfying accounts of how stages of processing work (e.g., Banks, 1983). We postulate recognition, memory search, and response selection stages but are chided for not delineating the exact nature of processing within any of these stages. As a reply to this criticism and as an illustration of the value of information-processing theory and strong inference in psychological inquiry, I review the research we have carried out on speech perception by ear and eye. The enterprise demonstrates how pure laboratory research can be designed to test between fundamentally different explanations and can facilitate the development of formal models of individual processing stages.

The processing of auditory and visual information in speech perception provides a relevant example of the apparent confounding of cues in the natural situation. One might expect that the validity and reliability of these two cues would be perfectly correlated. However, variation and noise in the environment and in the sensory systems could differentially modify the two sources of information and how they are processed. For example, the perceiver might have a varying view of the speaker's face and extraneous background noise might fluctuate randomly over time. Thus, for any particular speech event, the informativeness of the auditory aspect of the speech event is not necessarily correlated with that of the visual aspect of the event.

SPEECH PERCEPTION BY EYE AND EAR

The phenomenon stimulating this research has come to be known as the McGurk effect. McGurk and MacDonald (1976) reported a perceptual illusion when a given speech sound is dubbed onto a videotape of a different articulation. As an example, subjects reported *hearing* /da/ when the sound /ba/ was paired with a /ga/ articulation. Hearing was influenced by the corresponding visual information. As an aside, it should be noted that this discovery was only possible because of devising a situation that would not occur naturally. Thus, we have a violation of Brunswik's (1952) and Neisser's (1976) dicta for psychological research. What I aim to demonstrate is that the dissection of this phenomenon within the framework of binary oppositions, combined with the tools of information integration (Anderson, 1981, 1982) and model testing, illuminates not only the phenomenon itself but also more general problems of perception and pattern recognition.

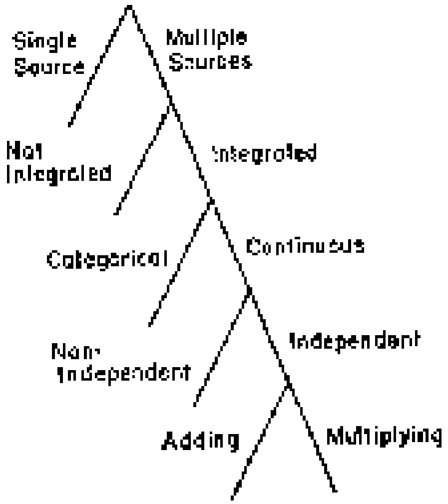

FIG. 11.2 Tree of wisdom illustrating binary oppositions central to the domain of speech perception by eye and ear.

The binary oppositions to be considered are arranged hierarchically in Fig. 11.2. In some cases, the question at one level is dependent on the answers to the questions at higher levels. As an example, the issue of whether or not multiple sources of information are integrated (combined) in perception requires that multiple sources rather than just a single source be available to the perceiver.

Single Versus Multiple Sources

The argument in favor of multiple sources of information in speech perception comes from the discovery of many different cues or features that contribute to the discriminable contrasts found in speech. The perceived distinction between voiced and voiceless English stop consonants in medial position such as /aga/ and /aka/ can be influenced by the preceding vowel duration, the silent closure interval, the voice-onset time, and the onset frequency of the fundamental. In addition to these bottom-up sources, phonological and semantic constraints function as top-down sources in recognition (Massaro & Cohen, 1983c; Tyler & Wessels, 1983).

The question addressed here is whether visual information also contributes to understanding speech. Anecdotal evidence comes from our dislike of dubbed movies and the seemingly extra effort to converse by telephone and to listen to narrative over the radio. The habit of watching a person speaking and the greater reliance on the speaker's visible articulations within noisy and distracting environments and with hearing loss also contribute to the impression of the visible domain of speech. A recent report provides some evidence that infants have some knowledge about the correspondence between the auditory and visual dimensions of the vowels /i/ and /a/ (Kuhl & Meltzoff, 1982). Although visual speech does not distinguish among all speech contrasts, it is ecologically valid to some degree. Of course, our question is whether visual speech is also functionally valid; that is, is it utilized by the perceiver. The McGurk effect seems to provide the most direct affirmative answer. What we see clearly influences but does not completely determine what we perceive in speech perception.

Integration Versus Nonintegration

The outcome of our first contrast indicates that both auditory and visual sources of information are utilized in speech perception. The answer to the next question might seem obvious to some because it is only natural for some to believe that the two sources are integrated. Integration of two sources of information refers to some process of combining or utilizing both sources to make a perceptual judgment. However, demonstrating that two sources are integrated in perceptual recognition is no easy matter. Consider a hypothetical experiment manipulating two independent cues to some distinction such as the height and width of rectangles as cues to their area (Anderson & Cuneo, 1978). Overall judgments of the area of the rectangles might reveal significant effects of both height and width even though these two cues were not integrated in the judgment of area. Some of the subjects may have used one cue, and other subjects may have used the other. Alternatively, a given subject may have used one cue on some trials and the other cue on other trials. Thus, a mixture of trials resulting from judgments on just a single cue can give results identical to that expected from a true integration of the two cues on each trial.

The two possible strategies of utilizing just one dimension versus integrating two dimensions are even more difficult to distinguish when the responses are discrete identification judgments rather than ratings. With discrete judgments, it might be impossible to eliminate the hypothesis of the single-cue strategy if subjects are tested only with a factorial combination of the cues. If it is possible to include discrete judgments of the single-cue conditions, however, the alternative explanations might be tested. Consider the perception of bimodal speech events created by the combination of synthetic speech sounds along an auditory /ba/ to /da/ continuum paired with /ba/ or /da/ visual articulations. By adding the single auditory and single visual cue conditions to the factorial design as illustrated in Fig. 11.3, it is at least logically possible to reject the mixed-single-cue strategy. What is necessary is to find judgments of certain bimodal speech events that are not equivalent to judgments of either the visual or auditory dimensions presented alone.

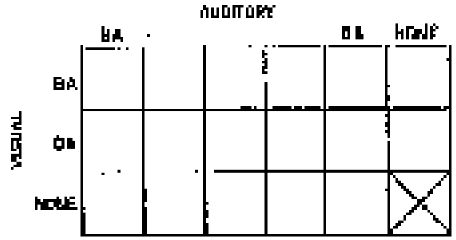

FIG. 11.3 Expansion of a typical factorial design to include single-auditory and single-visual cue conditions. The five levels along the auditory continuum represent speech sounds varying in equal steps between BA and DA. The BA and DA levels along the visual continuum represent BA and DA articulations. The level NONE for both the auditory and visual continua represents no information from that continuum.

Subjects were asked to identify bimodal speech events, auditory alone, and visual alone trials as illustrated in Fig. 11.3. The subjects were permitted an open-ended set of response alternatives. The results in Fig. 11.4 provide strong evidence against the mixed-single-cue strategy and for a true integration of the auditory and visual sources. The critical finding is the large proportion of /bda/ judgments given a visual /ba/ and an auditory /da/ when this same judgment is seldom given to either the visual or auditory information presented alone. We find over five times as many /bda/ judgments given to the bimodal events than to the visual-only condition, and the auditory-only condition almost never produces /bda/ judgments. It follows that the /bda/ judgments observed on bimodal trials could not have resulted from just one of the two sources and accordingly represent the outcome of the integration of both auditory and visual sources of information.

Evidence for the integration of auditory and visual information in bimodal speech perception also comes from the relative inability of subjects to selectively process either the auditory or visual dimensions of the speech event. Subjects were tested in three different conditions in the bimodal speech perception task. In one condition, subjects were instructed to identify the speech event as /ba/ or /da/ in terms of the information provided by *both* the visual and auditory sources of information. In the auditory selective attention condition, subjects were in-

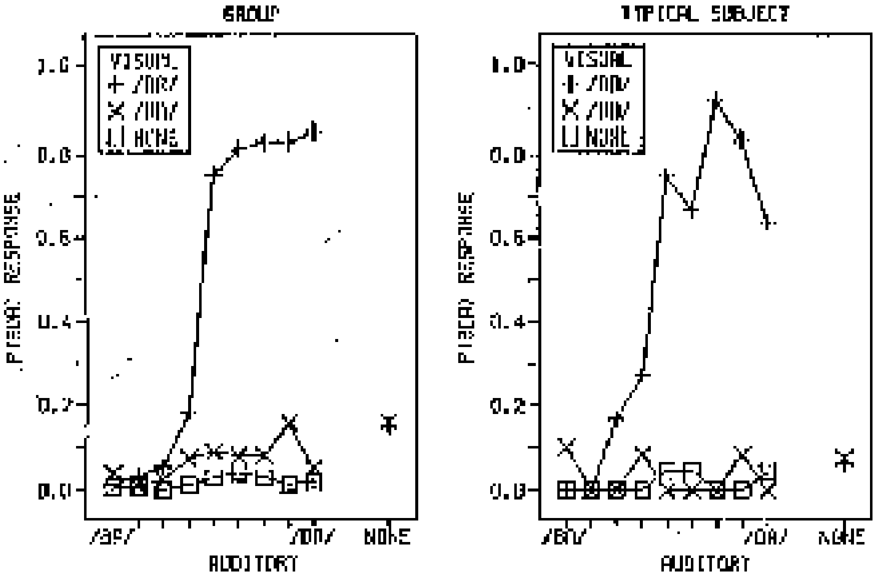

FIG. 11.4 Probability of /da/ judgments to bimodal, auditory, and visual speech events. The left panel gives the group results, and the right panel gives the results for a typical subject. The nine levels between BA and DA along the auditory continuum represent speech sounds varying in equal steps between BA and DA and the Level None corresponds to no auditory speech (the visual condition).

structed to base their decision on only the auditory information, even though they were required to watch the speaker on the videotape. In the visual selective attention condition, subjects were instructed to base their identification decision on only the visual source of information, even though they would also hear auditory information for each speech event. In all conditions, subjects were limited to the response alternatives /ba/ and /da/.

Fig. 11.5 presents the results under two different attention conditions. The "Both" panel represents performance in terms of the probability of a /da/ identification as a function of the visual and auditory sources of information when subjects were instructed to make their decision of what was said on the basis of both sources. As can be seen, there is a strong effect of both variables. The right "Auditory" panel corresponds to the results when subjects were instructed to make their decision of what they heard on the basis of only the auditory information. There is only a small difference between these two conditions. Subjects are influenced by the visual information almost as much when they are told to selectively process just the auditory source as opposed to being told to process both sources of information. The right "Visual" panel in Fig. 11.6 presents the analogous results when subjects were instructed to make their decision of what they saw on the basis of only the visual information. Although the influence of the auditory source seems to be somewhat attenuated in the visual selective attention conditions relative to the "Both" condition, there is still a substantial influence of the auditory information on the visual judgments. Thus, some integration occurs even though subjects attempt to process selectively only one of the two dimensions of input. These results indicate that subjects were not able to process selectively one dimension independently of influence of the other dimension. At least some integration appears to occur even against intentional selective attention.

One might argue that these results do not represent a definitive demonstration of integration. Even when subjects are instructed to report only what they heard, they might make their judgment on the basis of only the visual source on some subset of trials. This explanation seems unlikely, however, given that nonintegrated sources should be much easier to select than integrated ones. Furthermore, we might expect much larger differences in the selective and nonselective conditions if the sources have not been integrated. Our conclusion in favor of integration is furthered strengthened by the similar conclusion reached in the task with open-ended response alternatives.

The influence of both sources of information regardless of the set of the subject is another instance in which perceivers are not able to selectively process a single aspect of their perceptual world. This result is reminiscent of the Stroop effect (Stroop, 1935) in which the meaning of a word influences the pronuncia-

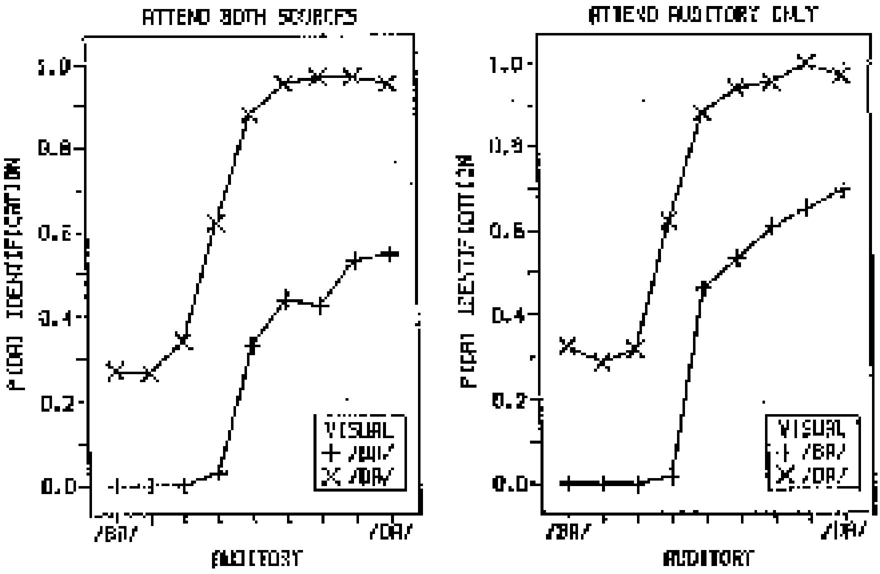

FIG. 11.6 Probability of a /da/ identification as a function of the auditory and visual sources of information under two attention conditions.

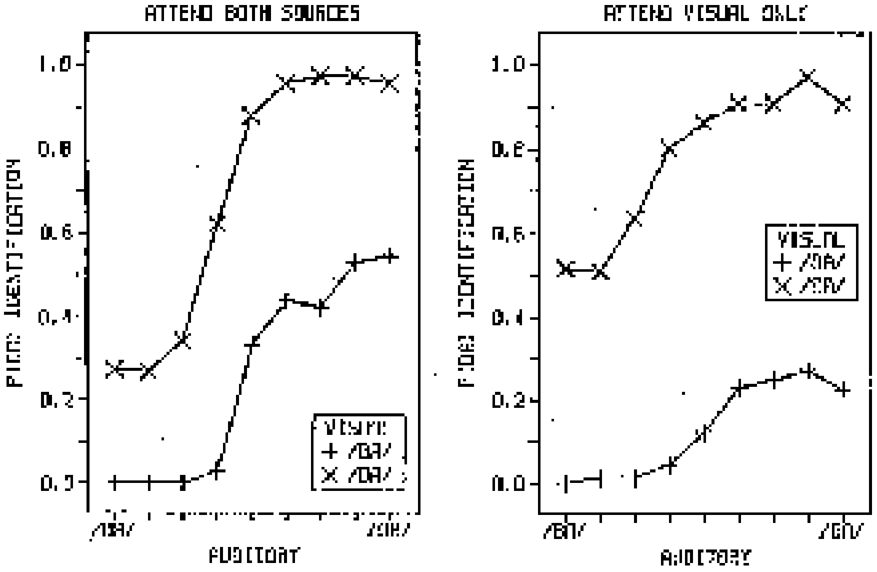

FIG. 11.8 Probability of a /da/ identification as a function of the auditory and visual sources of information under two attention conditions.

tion of the color of the type that the word is printed in. With respect to perception and action in the real world, this result at first glance might seem to be an inefficient way to design a perceptual mechanism. One would think that selectivity would be more optimal in the analysis of our perceptual world; however, if the perceptual world usually contains multiple sources of information, then selectivity can only be damaging to perceptual interpretation.

Given multiple sources of information, the more optimal strategy would be to evaluate and integrate all of the sources of information even though many of the sources at any one time may be ambiguous. The cost to a system designed as such would be the relative inability to process selectively single aspects or single dimensions of the perceptual world. In natural situations, the difficulty of selectivity is not usually a problem because we have available gross motor movements such as head and eye movements that allow us to selectively expose various sources of information. What these results demonstrate is that within a given view of the perceptual world, we find it difficult to selectively process one dimension independent of the influence of others.

Categorical Versus Continuous Information

The next branch on our tree of wisdom concerns the nature of the information available from each source. Categorical information implies that a discrete (phonetic) decision is obtained from each source before the sources of information are integrated. Continuous information implies that continuous information is available from each source for the integration process. Although these two hypotheses might seem to be easily distinguished, in reality, they are not. If only visual or auditory information is varied, the discrete as well as the continuous hypothesis can predict a continuous change in identification responses or rating responses with continuous changes along the stimulus dimension (Massaro & Cohen, 1983a).

A discriminating test between the hypotheses requires an analysis of the distribution of rating responses to repeated presentations of a stimulus event. Consider the bimodal speech events illustrated in Fig. 11.3 and the task of the subject is to rate each event along a nine point /ba/ to /da/ continuum. Categorical information predicts that the ratings to repeated presentations of a single event will come from two kinds of trials: those trials on which the event was identified as one alternative /ba/ and those on which the event was identified as the other alternative /da/. Thus, categorical perception predicts that the distribution of ratings to a given stimulus is a result of two different phonetic categorizations or a mixture of /ba/ identification and /da/ identification trials. On the other hand, continuous perception predicts that the rating is based on the outcome of the integration of the continuous auditory and visual sources of information. Hence, the distribution of ratings to a given speech event will result from a single kind of trial on which the perceiver has continuous information about the speech events.

Distributions of Rating Responses

As noted by Massaro and Cohen (1983a), analyzing the distribution of ratings can test between categorical and continuous models of speech perception. Fig. 11.7 gives the distribution of ratings for a typical subject in an experiment in which subjects were required to rate the /ba/-ness to /da/-ness along a 9-point scale. As can be seen in the figure, it is very difficult to see how these ratings could have resulted from a mixture of two different distributions. The categorical and continuous models were quantified to predict the distribution of ratings under the various experimental conditions. For all subjects, the continuous model gave a much better description of the results than did the categorical model. Thus we have evidence based on the distribution of ratings that the information along each dimension is perceived continuously rather than categorically.

Testings Models

Taking a second tack, Massaro and Cohen (1983b) and Massaro (1984a) formulated mathematical models of categorical and continuous perception of bimodal speech. The design involved a visual /ba/, visual /da/, or no visual articulation crossed with nine synthesized speech sounds equally spaced along a /ba/–/da/ continuum. Subjects watched and listened to presentations of the 27 aural-visual

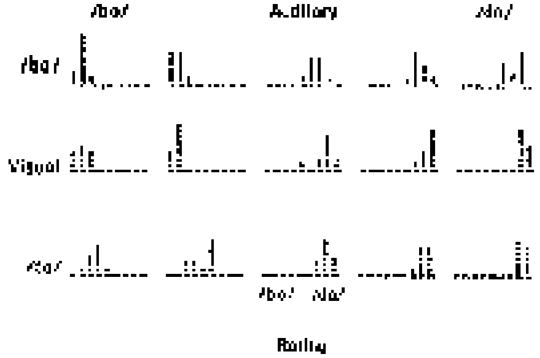

FIG. 11.7 Frequency distributions of ratings to bimodal speech events for a typical subject. The results are given for five levels along the synthetic speech auditory continuum between /ba/ and /da/ crossed with three levels along the visual continuum corresponding to a /ba/ articulation, an articulation, and a /da/ articulation. The ratings were on a 9-point scale between /ba/ and /da/. The categorical model predicts that repeated ratings to a given speech event result from two distributions, whereas the continuous model predicts that the ratings result from a single distribution.

events and identified the events as /ba/ or /da/ on each trial. We now derive the predictions of the two models for this experimental task.

Categorical Model. Following the logic of previous views of categorical perception, it is reasonable to assume that each dimension of the speech event is categorically perceived. There have been many conclusions that the auditory place continuum between /b/ and /d/ is perceived categorically (Eimas, 1963; Liberman, Harris, Hoffman, & Griffith, 1957; Repp, 1984). A similar logic might apply to the visual information (MacDonald & McGurk, 1978). According to a categorical model based on this logic, the listener has only categorical information representing the auditory and visual dimensions of the speech event. This model implies that separate categorical (phonetic) decisions are made to the auditory and visual sources and that these decisions are subsequently integrated (MacDonald & McGurk, 1978).

In the identification task, separate /da/ or /ba/ decisions would be made to both the auditory and visual sources and the identification response would be based on these separate decisions. Given categorical information from each dimension, there are only four possible outcomes for a particular combination of auditory and visual information: /da/-/da/, /da/-/ba/, /ba/-/da/, or /ba/-/ba/. If the two decisions to a given speech event agree, the identification response can follow either source. If the two decisions disagree, it is reasonable to assume that the subject will respond with the decision of the auditory source on some proportion p of the trials, and respond with the decision of the visual source on the remainder $(1 - p)$ of the trials. In this conceptualization, the magnitude of p relative to $(1 - p)$ reflects the relative dominance of the auditory source.

The probability of a /da/ identification response, P(D), given a particular auditory/visual speech event, A_iV_j, would be:

$$
\begin{aligned}
P(D{:}A_iV_j) &= \{1a_iv_j\} + \{pa_i(1 - v_j)\} \\
&\quad - [(1 - p)(1 - a_i)v_j\} + \{0(1 - a_i)(1 - v_j)\} \\
&= pa_i + (1 - p)v_j
\end{aligned}
$$

where i and j index the levels of the auditory and visual stimuli, respectively. The a_i value represents the probability of a /da/ decision given the auditory level i and v_j is the probability of a /da/ decision given the visual level j. Each of the four terms in the equation represents the likelihood of one of the four possible outcomes of the separate decisions multiplied by the probability of a /da/ identification response given that outcome. In the experiment, nine auditory levels are factorially combined with three visual levels. In this model, each unique level of the auditory stimulus would require a unique parameter a_i, and analogously for v_j. Because p reflects a decision variable, its value also required a unique parameter that would be constant across all stimulus conditions. Thus, a total of 9 + 3 + 1 = 13 parameters must be estimated for the 27 independent conditions.

Continuous Model. The continuous model will be formulated in terms of a fuzzy logical model of perception (Massaro & Cohen, 1983b; Oden & Massaro, 1978). Applying the model to the present task using auditory and visual speech, both sources are assumed to provide independent evidence for the alternatives /ba/ and /da/. Defining the onsets of the second (F2) and third (F3) formants as the important auditory cues and the degree of initial opening of the lips as the important visual cue, the prototypes are

/da/ : Slightly falling F2-F3 & Open lips

/ba/ : Rising F2-F3 & Closed lips

Given a prototype's *independent* specifications for the auditory and visual sources, the value of one source can not change the value of the other source at the prototype matching stage. In addition, the negation of a feature is defined as the additive complement; that is, we can represent Rising F2–F3 as 1-Slightly falling F2–F3) and Closed Lips as (1-Open lips),

/da/ : Slightly falling F2-F3 & Open lips

/ba/ : (1-Slightly falling F2-F3) & (1-Open lips).

The integration of the features defining each prototype is evaluated according to the product of the feature values. If a_i represents the degree to which the auditory

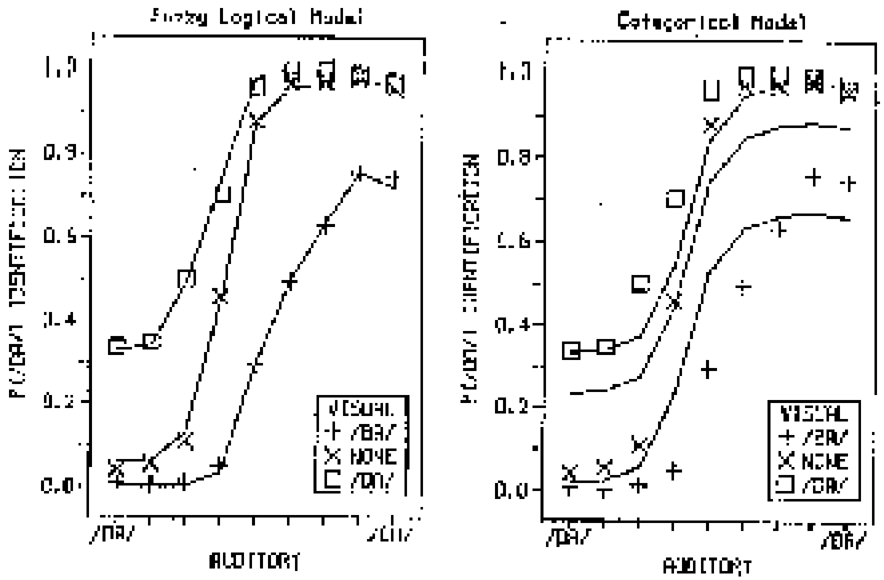

FIG. 11.8 Proportion (points) of /da/ identifications as a function of the auditory and visual levels of bimodal speech. The lines in the left panel give the predictions based on continuous perception of each source, whereas the predictions for categorical perception are given in the right panel.

stimulus A_i has Slightly falling F2-F3 and v_j represents the degree to which the visual stimulus V_j has Open lips, the outcome of prototype matching would be:

/da/ : $a_i v_j$

/ba/ : $(1 - a_i)(1 - v_j)$.

If these two prototypes are the only valid response alternatives, the pattern classification operation would determine their relative merit leading to the prediction that

$$P(D{:}A_iV_j) = \frac{a_i v_j}{a_i v_j + [(1-a_i)(1-v_j)]}$$

Given nine levels of A_i and three levels of V_j in the present task, the predictions of the model require $9 + 3 = 12$ parameters, one less than the categorical model.

Experimental Test. The points in Fig. 11.8 give the proportion of /da/ identifications as a function of the auditory level; the curve parameter is the visual condition. Both the auditory and visual sources influenced identification, with the contribution of visual source larger at the middle range of the auditory continuum. The lines in the left panel of Fig. 11.8 give the average predictions of the continuous model applied to the individual results of each of seven subjects. The right panel gives the predictions for the categorical model. As can be seen in the figure, the continuous model gave a significantly better account of the identification judgments than did the categorical model (Massaro & Cohen, 1983b). The advantage of the continuous model over the categorical model is preserved when the number of both stimulus and response alternatives is increased.

Independent Versus Nonindependent Evaluation of Sources

The next branch of the binary opposition tree involves the issue of whether the two sources of information are nonindependent or independent. Independent sources of information imply that the information value determined in the evaluation of one source remains independent of the information value of the other. Nonindependent sources implies a violation of this principle. There are two approaches we have taken to answer this question. One of them is model free and the other is model dependent. In the model-free test, we have used reaction times to the single dimension and bimodal events to determine whether the two dimensions show some form of intersensory interaction. If they do, then it should not be possible to account for the reaction times to a bimodal /ba/ in terms of simply the reaction times to a visual /ba/ and to an auditory /ba/. If the two dimensions are independent, we might expect reaction times to the bimodal event to be somewhat faster than those to the single-dimension events, but the advantage should be completely accounted for by statistical facilitation (Gielen, Schmidt, & Van Den Heuvel, 1983; Raab, 1962).

The reader might have realized that the predictions of independence appear to contradict those of integration; that is, the independence prediction implies that subjects respond to the auditory or visual source that is processed first, without waiting to integrate the two sources. Although this implication is correct, it does not necessarily mean that the two sources are not integrated, only that a response can be initiated before integration occurs. In the present task, the auditory and visual sources are completely unambiguous and they always agree with one another in the bimodal condition. Subjects are also instructed to respond as quickly as possible. Thus, although integration may still have occurred, it might not be observed in the reaction times because subjects could initiate a response based on just a single dimension whether or not integration of the two dimensions was complete.

Fig. 11.9 shows the distributions of reaction times of two subjects to the six stimuli. As can be seen in the figure, the subject is somewhat faster to the bimodal speech event but no faster than expected if the subject simply begins to initiate a response when either the auditory or visual dimension is identified. The advantage of bimodal trials can be accounted for simply in terms of the variability of the processing times along each dimension allowing the average reac-

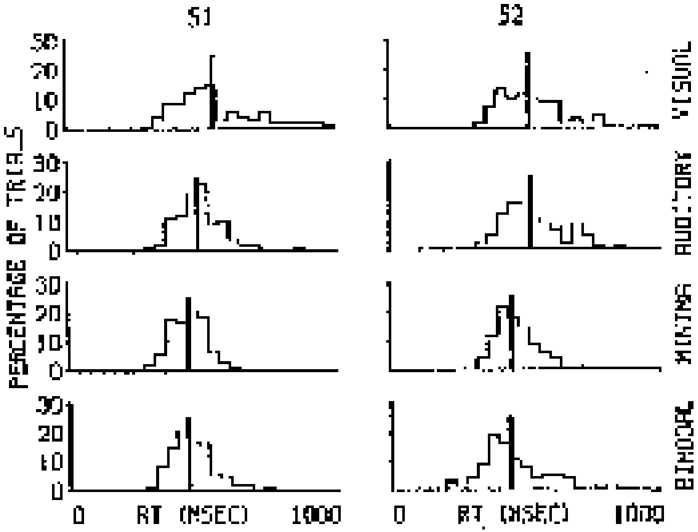

FIG. 11.9 Distribution of reaction times (RTs) for two subjects S1 and S2 to visual alone, auditory alone, and bimodal speech events. The minima distribution is that predicted for bimodal trials based on the auditory alone and visual alone trials. The solid bar gives the mean reaction time.

tion time to bimodal events to be shorter than to either dimension presented alone. These results also do not contradict the earlier conclusion that the two sources of information are integrated for perceptual recognition.

For the model-dependent test of the independence issue, we can ask whether a model assuming independence of auditory and visual information provides an adequate account of bimodal speech perception. The hypothesis of nonindependence must predict a failure of any model assuming independence (unless for some strange reason the independence model is mathematically equivalent to the nonindependence that exists). Independence models must assume that the information obtained along one source is independent of the information obtained along the other source. The models described in the test between categorical and continuous sources of information are independence models. Both models must fail if the auditory and visual sources are nonindependent. However, the adequate description of the continuous model provides evidence for independence and against nonindependence of auditory and visual information in speech perception.

Additive Versus Multiplicative Integration

The final branch to be discussed in this chapter involves the combination rule used to integrate the two sources. An additive or averaging rule is usually the first to come to mind given the seminal work of Anderson and his colleagues (Anderson, 1981, 1982). This integration rule makes a strong prediction concerning the average rating response in an information-integration task; if the scale is an interval one, then the plot of the two factors should produce parallel curves. The theoretical reason to question the applicability of adding or averaging the evaluations of the separate sources of information is that this combination rule is nonoptimal. Averaging an ambiguous source of information with an informative source will tend to neutralize the judgment relative to the informative dimension being presented alone. In contrast, multiplying the sources of information within the context of the continuous model (Massaro, 1984a, 1984b, 1984c; Oden & Massaro, 1978) is functionally identical to Bayes rule and the Likelihood Ratio.

A test of the additive rule can be made in an experiment in which subjects rated on a 9-point scale bimodal speech events. The auditory source was varied along a continuum of nine steps between /ba/ and /da/ and the visual source could be /ba/, neutral, or /da/ articulations. Fig. 11.10 gives the results of a typical subject in the experiment along with the predictions of additive and multiplicative integration rules. As can be seen in the figure, the results contradict the parallelism prediction of the additive rule. The results reflect instead that

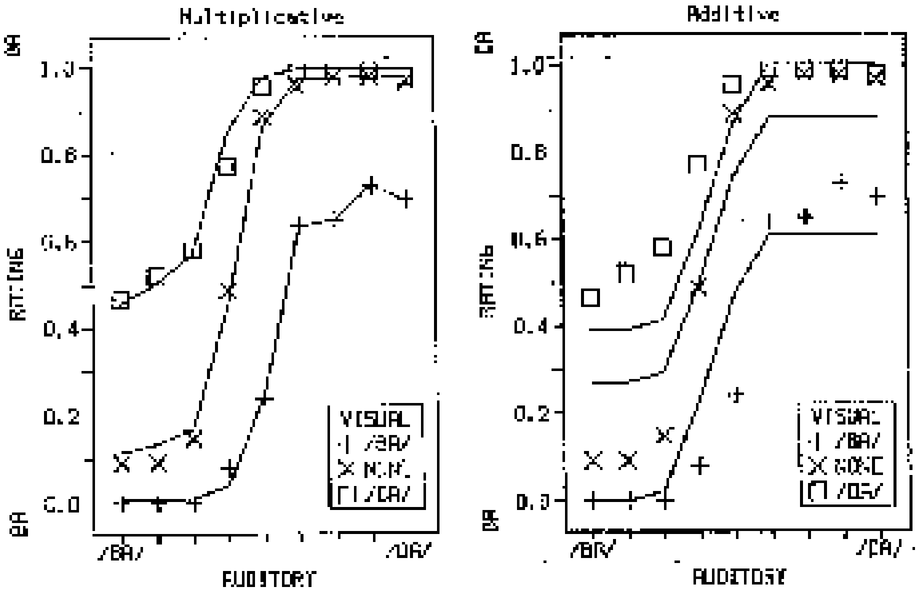

FIG. 11.10 Observed (points) rating judgments for a typical subject as a function of the auditory and visual levels of bimodal speech. The lines in the left panel give the predictions for a multiplicative integration rule, whereas the predictions for an additive integration rule are given in the right panel.

the contribution of one source has more of an impact to the extent the other source is ambiguous.

CONCLUSION

This short review of research carried out within the framework of information processing and strong inference should inform the introductory discussion concerning research paradigms for psychological inquiry. I discussed how the information-processing framework could be expanded to study the information that is used in information processing. The questions proposed in Fig. 11.2 could not have been answered in representative designs. As an example, only by manipulating the auditory and visual sources independently was it possible to assess whether the two sources are integrated in perceptual recognition. A factorial combination of the sources also allowed us to determine the categorical versus continuous nature of each source, whether the sources are evaluated independently, and how the sources are integrated in perception. Additional studies that cannot be discussed here have addressed the questions of the relative influence of each source and developmental and individual differences in perception. With respect to Neisser's (1976) concern for natural problems, artificial experiments can be highly informative. Because one does not find independent variation of auditory and visual sources of information in natural speech, both Neisser and Brunswik would have to frown on the method of our research enterprise.

I believe that the enterprise was fruitful in providing insights into fundamental issues in perception and action. Although this enterprise might seem far removed from the book's theme of the relationship between perception and action, it makes apparent that perception involves the evaluation and integration of multiple sources of information. Theories of perception in the service of action must confront the important issues centered around how action is guided by the evaluation and integration of multiple sources of information. Although the laboratory is a far cry from nature, a good theory can bridge the gap between the two so that the distance seems shorter and shorter with every step.

ACKNOWLEDGMENTS

The writing of this chapter and the research reported in the chapter were supported, in part, by NINCDS Grant 20314 from the Public Health Service and Grant BNS-83-15192 from the National Science Foundation. The finishing touches on this chapter were completed while the author was a member of the project "Perception and Action," at the Zentrum fur Interdisziplinare Forschung der Universitat Bielefeld, Bielefeld, West Germany. The author would like to thank the other members of the group and the Institute for providing an ideal environment for scholarship. Michael Cohen made important contributions to the experimental work and Roy Gibbs, Herbert Heuer, and Andries Sanders provided helpful comments on a earlier draft of the chapter.

REFERENCES

Allport, D. A. (1980). Patterns and actions: Cognitive mechanisms are content specific. In G. Claxton (Ed.), *Cognitive psychology: New directions.* London: Routledge & Kegan Paul.

Anderson, N. H. (1981). *Foundations of information integration theory.* New York: Academic Press.

Anderson, N. H. (1982). *Methods of information integration theory.* New York: Academic Press.

Anderson, N. H., & Cuneo, D. O. (1978). The height + width rule in children's judgments of quantity. *Journal of Experimental Psychology: General, 107,* 335–378.

Banks, W. P. (1983). On the decay of the icon. *The Behavioral and Brain Sciences, 6,* 14–15.

Broadbent, D. E. (1958). *Perception and communication.* New York: Pergamon Press.

Broadbent, D. E. (1971). *Decision and Stress.* New York: Academic Press.

Brunswik, E. (1944). Distal focussing of perception: Size-constancy in a representative sample of situations. *Psychological Monographs, 56* (Whole No. 254), 1–49.

Brunswik, E. (1952). *The conceptual framework of psychology.* Chicago: University of Chicago press.

Brunswik, E. (1955). Representative design and probabilistic theory in a functional psychology. *Psychological Review, 62,* 193–217.

Brunswik, E. (1956). *Perception and the representative design of psychological experiments.* Berkeley: University of California press.

Brunswik, E., & Kamiya, J. (1953). Ecological cue validity of "proximity" and of other Gestalt factors. *American Journal of Psychology, 66,* 20–32.

Cutting, J. E., & Millard, R. T. (1984). Three gradients and the perception of flat and curved surfaces. *Journal of Experimental Psychology: General, 113,* 198–216.

Eimas, P. D. (1963). The relation between identification and discrimination along speech and non-speech continua. *Language and Speech, 6,* 206–217.

Fechner, G. T. (1966). *Elements of Psychophysics* (Vol. 1). H. E. Adler, D. H. Howes, & E. G. Boring, (Eds. and Trans.). New York: Holt, Rinehart, & Winston. (original work published 1860)

Fodor, J. A. (1983). *The modularity of mind: An essay on faculty psychology.* Cambridge: Bradford books.

Gibson, J. J. (1979). *The ecological approach to visual perception.* Boston: Houghton Mifflin.

Gielen, S. C., Schmidt, R. A., & Van Den Heuvel, P. J. M. (1983). On the nature of intersensory facilitation of reaction time. *Perception and Psychophysics, 34,* 161–168.

Gopher, D., & Sanders, A. F. (1984). S-Oh R: Oh stages! Oh resources! In W. Prinz & A. F. Sanders (Eds.), *Cognition and motor processes.* Berlin: Springer–Verlag.

Haber, R. N. (1983). The impending demise of the icon: A critique of the concept of iconic storage in visual information processing. *The Behavioral and Brain Sciences, 6,* 1–11.

Helmholtz, H. von (1962). *Treatise on physiological optics* (3rd ed.). J. P. C. Southall (Ed. and Trans.). New York: Dover. (original work published 1856–1866).

Jenkins, J. J. (1979). Four points to remember: A tetrahedral model of memory experiments. In L. S. Cermak & F. I. M. Craik (Eds.) *Levels of processing in human memory.* Hillsdale, NJ: Lawrence Erlbaum Associates.

Jenkins, J. J. (1980). Can we have a fruitful cognitive psychology? In *Nebraska symposium on motivation.* University of Nebraska Press.

Kuhl, P. K., & Meltzoff, A. N. (1982). The bimodal perception of speech in infancy. *Science, 218,* 1138–1141.

Kuhn, T. S. (1970). *The structure of scientific revolutions.* Chicago: University of Chicago press.

Liberman, A. M., Harris, K. S., Hoffman, H. S., & Griffith, B. C. (1957). The discrimination of speech sounds within and across phoneme boundaries. *Journal of Experimental Psychology, 54,* 358–368.

MacDonald, J., & McGurk, H. (1978). Visual influences on speech perception processes. *Perception & Psychophysics, 24,* 253–257.

Massaro, D. W. (1975a). *Experimental psychology and information processing*. Chicago: Rand–McNally.

Massaro, D. W. (Ed.). (1975b). *Understanding language: An information processing analysis of speech perception, reading and psycholinguistics*. New York: Academic Press.

Massaro, D. W. (1978). A stage model of reading and listening. *Visible Language, 12*, 3–26.

Massaro, D. W. (1979). Reading and listening (Tutorial paper). In P. A. Kolers, M. Wrolstad, & H. Bouma (Eds.), *Processing of visible language* (Vol. 1, pp. 331–354). New York: Plenum.

Massaro, D. W. (1984a). Children's perception of visual and auditory speech. *Child Development, 55*, 1777–1788.

Massaro, D. W. (1984b). Time's role for information, processing, and normalization. In J. Gibbon & L. Allan (Eds.), *Timing and time perception* (Vol. 423, pp. 372–384). New York: Annals of the New York Academy of Sciences.

Massaro, D. W. (1984c). Building and testing models of reading processes: Examples from word recognition. In P. D. Pearson (Ed.), *Handbook of reading research*. New York: Longman.

Massaro, D. W., & Cohen, M. M. (1983a). Categorical or continuous speech perception: A new test. *Speech Communication, 2*, 15–35.

Massaro, D. W., & Cohen, M. M. (1983b). Evaluation and integration of visual and auditory information in speech perception. *Journal of Experimental Psychology: Human Perception and Performance, 9*, 753–771.

Massaro, D. W., & Cohen, M. M. (1983c). Phonological context in speech perception. *Perception and Psychophysics, 34*, 338–348.

McGurk, H., & MacDonald (1976). Hearing lips and seeing voices. *Nature, 264*, 746–748.

Neisser, U. (1967). *Cognitive psychology*. New York: Appleton-Century-Crofts.

Neisser, U. (1976). *Cognition and reality*. San Francisco: W. H. Freeman.

Newell, A. (1973). You can't play 20 questions with nature and win: Projective comments on the papers of this symposium. In W. G. Chase (Ed.), *Visual information processing*. New York: Academic Press.

Oden, G. C., & Massaro, D. W. (1978). Integration of featural information in speech perception. *Psychological Review, 85*, 172–191.

Platt, J. R. (1964). Strong inference. *Science, 146*, 347–353.

Popper, K. (1959). *The logic of scientific discovery*. New York: Basic Books.

Raab, D. H. (1962). Statistical facilitation of simple reaction times. *Transactions of the New York Academy of Sciences, 24*, 574–590.

Repp, B. H. (1984). Categorical perception: Issues, methods, findings. In N. J. Lass (Ed.), *Speech and language: Advances in basic research and practice* (Vol. 10). New York: Academic Press.

Rock, I. (1975). *An introduction to perception*. New York: Macmillan.

Sanders, A. F. (1980). Stage analysis of reaction processes. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 331–354). The Netherlands: North-Holland Publishing.

Sanders, A. F. (1984). Ten Symposia on Attention and performance: Some issues and trends. In H. Bouma & D. G. Bouwhuis (Eds.), *Attention and performance X: Control of language processes*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Stelmach, G. E., & Hughes, B. G. (1984). Cognitivism and future theories of action: Some basic issues. In W. Prinz & A. F. Sanders (Eds.), *Cognition and motor processes*. Berlin, Heidelberg: Springer-Verlag.

Sternberg, S. (1969). The discovery of processing stages: Extensions of Donder's method. *Acta Psychologica, 30*, 276–315.

Sternberg, S. (1975). Memory scanning: New findings and current controversies. *Quarterly Journal of Experimental Psychology, 27*, 1–32.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*, 643–662.

Theios, J. (1975). The components of response latency in simple human information processing tasks. In P. M. A. Rabbitt & S. Dornic (Eds.), *Attention and performance*. London: Academic Press.

Tolman, E. C. (1956). Egon Brunswik: 1903–1955. *American Journal of Psychology, 69*, 315–324.

Tulving, E. (1979). Memory research: What kind of progress? In L.-G. Nilsson (Ed.), *Perspectives on memory research: Essays in honor of Uppsala University's 500th Anniversary*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Turvey, M. T. (1977). Contrasting orientations to the theory of visual information processing. *Psychological Review, 84*, 67–88.

Turvey, M. T., & Shaw, R. (1979). The primacy of perceiving: An ecological reformulation of perception as a point of departure for understanding memory. In L.-G. Nilsson (Ed.), *Perspectives on memory research: Essays in honor of Uppsala University's 500th anniversary*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Tyler, L. K., & Wessels, J. (1983). Quantifying contextual contributions to word recognition processes. *Perception & Psychophysics, 34*, 409–420.

Zadeh, L. A. (1965). Fuzzy sets. *Information and Control, 8*, 338–353.