CHAPTER

2

The Theory of J. Pascual-Leone

COGNITIVE DEVELOPMENT AND COGNITIVE STYLE

The first systematic neo-Piagetian theory, the Theory of Constructive Operators (TCO), arose as an integration of two lines of inquiry: the Piagetian study of cognitive development and Witkin's study of field dependence. Juan Pascual-Leone (1969), hypothesizing that individual differences in cognitive style influence the appearance of Piagetian operations, proposed construction of a psychological theory compatible with the data of both schools. Pascual-Leone sought not simply to juxtapose the constructs of the two theories, but also to introduce new theoretical constructs allowing redefinition of the basic ideas of both theories *in the same language*. He sought as well to point out the structural analogies (where they exist) between Piagetian tasks and those created by Witkin.

Field Dependence/Independence

The concept of *cognitive style* refers to a dimension of cognitive processing along which people differ from one another. Examples include reflective and impulsive styles, convergent and divergent thinking, and the preference for use of broad or narrow categories. People tend to remain more or less faithful across diverse situations to their characteristic cognitive style. The concept of cognitive style is different from that of cognitive ability. Individual differences in cognitive style occur with respect to a bipolar scale;

therefore, saying that one person is "more reflective" than another is equivalent to saying that person is "less impulsive." One cannot call either the impulsive end or the reflective end of the bipolar scale "positive," given that in different situations, both the impulsive style and the reflective style have adaptive value. Individual differences in cognitive ability, however, occur with respect to a unipolar scale; and, clearly, it is more adaptive to be more able rather than less.

The specific cognitive style studied by Witkin et al. (Witkin, Dyk, Faterson, Goodenough, & Karp, 1974; Witkin, Goodenough, & Oltman, 1979; Witkin et al., 1954) is field-dependence/independence. According to Witkin, *field-dependent* perception is ruled by the overall organization of the surrounding perceptual field, the parts of which are dealt with as though fused together. In *field-independent* perception, however, one experiences the elements of the field as distinct from one another, even though the field has an overall structure. Witkin et al. (1954) primarily studied cognitive style differences in perceptual tasks. For example, participants were placed in a tilted room and asked to rotate their chair to bring themselves to a vertical position. Some individuals (labelled *field-independent*) reached the vertical almost exactly. Others were influenced by the surrounding perceptual field, that is by the inclination of the floor, walls and ceiling, to the extent that they positioned their seat obliquely such as to be leaning in the same direction as the incline of the walls. In another case, participants had to position a rod vertically within a perceptual field formed by an inclined frame. Another example, the embedded figures task, requires finding a simple figure within a larger more complex figure that is meaningful and designed in such a way as to reduce the saliency of the simpler figure. Field-dependent individuals find it difficult to disregard the complex figure and locate the requested detail rapidly.

Further studies (Witkin et al., 1974) demonstrate that field dependence is not simply a perceptual style, but a cognitive one in the full sense of that term.[1] Field-independent persons perform better on some intelligence test items that require analyzing and restructuring the stimulus field, for example, Wechsler's picture arrangement, block design, and picture completion. Moreover, field-independent individuals prove more adept at solving verbal problems that require restructuring the terms of the problem, that is, an insight that disregards a knowledge field composed of rules learned in a similar context, or a field based on "functional fixity" in the use of objects.

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[1] Despite the correlation with tests of ability, field-dependence/independence is considered a cognitive *style*. In fact, some perceptual tasks and certain social situations favor field-dependence (Witkin et al., 1974; Witkin, Goodenough, & Oltman, 1979). Skill in visual arts probably requires a set of abilities, some global in nature and others analytic.

Field-Dependence and Piagetian Tasks

Pascual-Leone (1969) hypothesizes a precise relationship between field dependence and certain Piagetian tasks. According to his hypothesis, tests of field dependence (and other tasks correlated with them) involve a cognitive conflict: prior knowledge or the perceptual characteristics of the stimuli tend to activate inappropriate strategies. Thus, one must exert attentional effort to activate appropriate knowledge and strategies as well as to overcome the effect of the misleading information. Many Piagetian tasks, according to Pascual-Leone, present the same type of conflict, and therefore should correlate with tests of field dependence.

Consider, for example, the classic Piagetian conservation tasks. In these, the child views two equal balls of clay, one of which is then flattened or elongated. After the transformation, the child is asked to judge whether one of the two contains more clay than the other, or if one is heavier, or if one would cause the water level in a container to rise more. The perceptual salience of the difference between the visible surfaces or the heights of the two objects and the child's past experience (which suggests that a wider or taller object is also heavier, contains more matter, etc.) constitute misleading information and tend to activate a strategy based on a perceptual comparison between the two objects as they appear in the moment. In order to provide a correct response, the child must instead attend simultaneously to several pieces of information: the initial equality of the balls, the transformation conducted, the fact that it did not involve adding or subtracting clay, and the fact that if two objects contain the same quantity of matter then their weights are also the same.

Similar considerations apply for other Piagetian tasks. When one asks children to compare the length of two zigzag paths, the straight-line distance between their end points constitutes a perceptually salient dimension that permits a rapid, but often incorrect, judgment. A correct strategy requires instead an integration of the lengths of the differently directed path segments.

The most salient information sometimes prompts responses that conflict with the correct one. For example, consider a child looking through a small window at a cylinder on which some pictures are drawn such that these pictures appear in the window one at a time (Piaget & Inhelder, 1966). Rotating the cylinder to the left, the child will say that the picture to be seen next is the picture that is to the left of the currently visible one. The child is fooled by the salience of rotation direction. In this case, too, discovering a correct rule requires coordination of various items of information: the order of the pictures, their cyclical positioning, and the direction of rotation of the cylinder with respect to the window.

In agreement with his hypotheses, Pascual-Leone finds that the performance of 10-year-olds on a set of Piagetian tasks, including those described here, correlates with their performance on tests of field independence and on the analytic tasks of Wechsler's test. Moreover, the experimental manipulation of salient but misleading pieces of information suggests that the field-dependent children are particularly influenced by these pieces. Pascual-Leone (1969) finds that field-dependent adults also commit occasional errors in these cognitive tasks.

Pascual-Leone's results, confirmed by further research (Huteau, 1980; Neimark, 1981; Pascual-Leone, 1989; Pascual-Leone & Morra, 1991) support the hypothesis of a structural similarity between field-independence tasks and certain Piagetian tasks. In both cases, a cognitive conflict must be resolved by coordinating relevant information that is not salient, rather than using information that is more salient or is familiar from past experience.

SCHEMES AND PROCESSING CAPACITY

As we have seen, Pascual-Leone emphasizes that success on Piagetian tasks requires keeping in mind various pieces of information simultaneously and coordinating them. Although Piaget explains cognitive development with changes in logical competence, Pascual-Leone suggests instead that the stage aspects of cognitive development are to be explained by increases in the capacity to coordinate information.

Processing Capacity: Hypotheses Regarding Its Limits and Development

The relevant pieces of information obviously differ from one task to another, and for this reason it is not possible to make comparisons among different tasks by defining units of information in an "objective" manner, for example, by analyzing stimulus attributes. It is from *the subject's point of view* that units of information are to be defined, namely by considering which mental operations or chunks of information constitute functional units. The concept of *scheme*, which Piaget (1936, 1967) characterizes as a functional whole, is particularly suitable for this purpose.

The concept of scheme is elaborated in the following section. Here we note only that, reinterpreting the corpus of Piagetian data, Pascual-Leone hypothesizes that with development children are able to coordinate an increasing number of schemes. In particular, for the cognitive acquisitions of the late preoperational period (5–6 years) the coordination of two schemes is required; most of the abilities typical of concrete operations

(7–8 years) require coordination of three schemes. The number becomes four for abilities acquired later (about 9 years) and five or more for the operations that Piaget called formal (de Ribaupierre & Pascual-Leone, 1979; Pascual-Leone, 1980; Pascual-Leone & Smith, 1969).[2] Pascual-Leone (1970) hypothesizes a mechanism that is able to attend to a certain number of schemes simultaneously, and this capacity increases one unit on average every 2 years up to the age of 15. At that age, the number is seven, which according to Miller (1956) characterizes the capacity of the human information processing system.

Research on the CSVI Task

In order to verify such hypotheses, which at that time constituted an interpretation of the Piagetian data that was both new and against the current, Pascual-Leone (1970) devised a new task substantially different from the Piagetian ones. In Pascual-Leone's task, the schemes are clearly defined *a priori* and are learned in the same manner by all the participants. These "artificial" schemes are constituted by stimulus–response pairings, such as: red—clap your hands, large figure—open your mouth, and so on. Once such pairs are learned, the main experimental task begins using complex visual stimuli (CSVI, *Compound Stimuli Visual Information task*). Children, between the ages of 5 and 11, are shown cards with a patterned drawing displaying two or more of the features for which they have learned paired responses. To minimize the possible influence of short-term memory the patterns are presented for a sufficiently long period (5 seconds) and the children can respond during the presentation, as well as immediately after. Pascual-Leone hypothesizes that children will respond to one or more features of a compound stimulus, in accordance with a probabilistic model.[3] The model has two parameters: the number of relevant features in the drawing, and the children's "central computing space," that is, the number of schemes that they are able to coordinate. Pascual-Leone (1970, 1978) finds that, as hypothesized, this number is two at 5 years of age and increases by one unit every 2 years. These results have been confirmed by several experiments with procedural variations (such as using response buttons rather than a set of motions, using sequential rather than simultaneous presentation of the characteristics for responding, and varying the duration of presentation; e.g., see de Ribaupierre et al., 1990; Globerson, 1983a; Miller, Bentley, & Pascual-Leone, 1989; Pascual-Leone, 1970).

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[2] The reference here is to the "classical" version of the Piagetian tasks. As seen in the first chapter, their experimental versions can involve different information loads.

[3] The model adopted is the Bose-Einstein distribution. Instead, Case and Serlin (1979) consider the distribution of Maxwell-Boltzmann more appropriate. These are described in various textbooks of probability theory (e.g., Feller, 1968).

Trabasso and Foellinger (1978) reexamined Pascual-Leone's (1970) model employing a short-term memory task involving gestures rather than the CSVI. Their results were sharply different from those of Pascual-Leone, and their experiment provoked an interesting and lively debate on the epistemological level (Pascual-Leone, 1978; Pascual-Leone & Sparkman, 1980; Trabasso, 1978). A comparison between the results of Pascual-Leone (1970, 1978) and those of Trabasso and Foellinger (1978) demonstrates that the CSVI is *not* a short-term memory task and that *limited processing capacity* and *short-term memory* are not synonymous concepts.

One variable that considerably influences performance on the CSVI is the task's familiarity, a characteristic that permits development of suitable attentional strategies (de Ribaupierre, 1993; Miller et al., 1989; Pascual-Leone, 1970; see also the following section of this chapter).

SCHEMES: DEFINITIONS AND PROPERTIES

To this point in the chapter, we have considered the research with which Pascual-Leone developed the basic insights of his theory. Now we consider how the formal aspects of the TCO have been developed. These aspects include two types of constructs: schemes (or subjective operators) and second-order (or metasubjective) operators.

The Components of Schemes

In this theory, the *scheme* is conceived as the unit of analysis of cognitive processes. Because this concept is fundamental, it is necessary to define it in more precise terms than those of Piaget. Also necessary are practical rules (see chap. 9) for identifying the schemes involved in a mental process.

A scheme, according to Piaget, is a set of the organism's reactions that are not necessarily observable, and that are tightly connected in a totality or whole. Activation of a scheme is possible in diverse situations ("assimilation" of reality by a scheme), but modification or differentiation ("accommodation") is also possible. Some schemes are innate, but the vast majority result from experience, from the capacity of human beings to abstract invariant properties from their activities and perceptual experiences. Accommodation and coordination of existing schemes are processes that normally lead to the acquisition of new schemes.

Pascual-Leone (1969, 1970; Pascual-Leone & Goodman, 1979; Pascual-Leone & Johnson, 1991) redefines more precisely the Piagetian concept, by postulating that each scheme has two, or in some cases three, components. The two essential components of every scheme are called the *releasing component* and the *effecting component*. The first is made up of the set of conditions that, *even if minimally satisfied*, initiate the scheme's activation. The second consists of the effect of its activation. The third component, called the *terminal component*, is found only in schemes that are organized according to a temporal sequence and is constituted of the conditions that bring the activation to an end.

Schemes can be, and usually are, organized hierarchically and recursively; one scheme could be made up of schemes that are in turn made up of schemes and so on. Often both the releasing component and the effecting component of a scheme are formed of lower level schemes.

The Properties of Schemes

Because even partial satisfaction[4] of the conditions of a scheme's releasing components is sufficient to activate that scheme, the tendency in any particular situation is toward the activation of many schemes. For example, on encountering the word *horse* while reading a book, the scheme of the corresponding lexical unit is activated. Its primary effect is to activate a representation of the word's pronunciation and meaning. But schemes corresponding to other lexical units orthographically similar to *horse* and sharing a certain number of activation conditions are also activated. Other schemes will have been activated by the phrase preceding the word *horse*, others by the differing significances associated with encountering the word in a novel as opposed to a zoology textbook, and still others by recent thoughts or experiences. The meaning of the activated lexical units could, in turn, be a part of the activating conditions of other more complex, higher level schemes—for example, schemes representing knights in chivalrous battle. Only a subset of the schemes is compatible with one another, however, and their compatibility enhances their activation, whereas the incompatible schemes inhibit one another. Thus, if an opera-loving reader encounters the word horse while a radio in the background is playing the music of Monteverdi, that reader may begin imagining Tancredi and Clorinda's duel, even if the word appears in a zoology text.

The preceding example illustrates several postulates proposed by Pascual-Leone and Goodman (1979), which we reformulate liberally as follows:

- Each activating condition included in a scheme's releasing component carries its own "activation weight." If a salient condition of a scheme or if a condition for which particular relevance has been learned is satisfied, the scheme's activation increases more than would occur with the

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[4] Other theories postulate cognitive units, such as the "productions" of Newell and Simon (1972), which are activated only if their conditions are completely satisfied.

satisfaction of a less salient condition whose importance had not been learned.[5]

- Activation of a scheme tends to diminish the activation of other schemes that are incompatible with it.[6]
- Activation of a scheme induces activation of higher level schemes for which that scheme is a condition of activation.[7]
- Activation of a scheme tends to increase the activation of other schemes that are compatible with it.[8]
- A person's mental processes and behavior are codetermined by the set of compatible schemes that are most active at a given moment. This final postulate is fundamental for the theory and is called the *schematic overdetermination principle*.

SCHEME CLASSIFICATION

Pascual-Leone (1976a, 1984, 1995; Pascual-Leone et al., 1978; Pascual-Leone & Johnson, 1991) classifies schemes according to three criteria: *modality, level*, and *type*.

Modality of Schemes. Classification by *modality*[9] is the most obvious. It refers to the scheme's content: visual schemes, auditory schemes, and so on, for recognizing stimuli in each sensory modality; linguistic schemes for understanding and producing language; affective schemes and personality schemes (conceptualized as complex, superordinate structures that coordinate a number of cognitive and affective schemes). In the affective schemes, according to the TCO, the effecting component is made up of

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[5] For example, if one has a scheme for puffin, seeing a puffin's beak (very salient) will be sufficient to recognize the bird. If the bird is too far away to allow identification of the beak, a condition with high activation weight could be the manner of flying, but only for a person who has had sufficient opportunity to learn this bird's flight. On the other hand, it is likely that the activation weight will be low for the feet because these are similar in other marine birds and not very salient.

[6] For example, schemes for eating and for blowing out the candles both tend to activate in the presence of a birthday cake, yet they are incompatible with each other in as much as their effecting components require movements that can not be carried out simultaneously.

[7] For example, activation, for whatever reason, of the scheme that represents the concept "cod" tends to activate the schemes for "fish," "animal," and "food."

[8] For example, for a person with a scheme for Macbeth's temptation, the schemes for "dagger," "darkness," and "witches" increment each other's activation because all three are constituents of that superordinate scheme.

[9] One of the main issues in neuropsychology and cognitive science is the study of representations of knowledge and the way in which these representations form modules, semantic areas or, at the least, cognitive domains. This issue is discussed more extensively in chapters 5–7.

physiological reactions (to turn pale with fear, to blush with embarrassment) or motivational reactions (for example, a motivational effect of fear is the activation of motor and cognitive schemes connected to flight). Cognitive schemes are divided into two broad categories, akin to the distinction usually made in cognitive psychology between propositional and analog representations.[10]

Abstraction Level. The second criterion of scheme classification is the *level of abstraction*. This criterion is based in the postulate that schemes are organized in a hierarchical and recursive manner, that is, that any scheme may be composed of other schemes. Thus, it is possible to order schemes according to successive levels of complexity and abstraction with the simplest perceptual and motor schemes (such as those that encode single visual input characteristics) at the base of the hierarchy. Pascual-Leone (1984) proposes detailed, though speculative, hypotheses on such a hierarchy. He suggests that in each cognitive domain there is a habitual, or *zero*, level, of representation (e.g., representations of objects) and that to activate schemes at levels more complex or more abstract than the zero level would require attentional effort. Similarly, he proposes that such effort would also be required in order to pay attention to components or features at a level more elementary than the habitual one; in other words, only with analytical effort would it be possible to activate elementary representations separately from the zero-level representations of which they are a habitual part.

Scheme Type. The third classification criterion, *types (or modes) of schemes*, concerns the distinction between figurative and operative knowledge[11] (Piaget & Inhelder, 1966). In brief, figurative schemes represent states and operative schemes represent transformations. Objects, configurations, concepts, meanings, mental states are represented in the mind as figurative schemes, whereas operative schemes represent actions, processes, operations, and transformations that beginning from one state generate another (Pascual-Leone et al., 1978; Pascual-Leone & Johnson, 1991).

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[10] Pascual-Leone (1976a, 1984, 1995) refers to these as *logological* (conceptual) and *mereological* (experiential) structures, respectively. The first would be formed of concepts, relations and propositions connected by rules with a syntactic form. It would involve substantial reduction of information with respect to the experiential data that it represents. The second, however, would be perceptual, spatial, temporal, motor, and intentional representations reflecting experiential knowledge, that includes much of the detail that one notices and the constraints that one meets in interactions with the realities in the environment. Conceptual and experiential structures tend to be stored respectively in the left and right hemisphere.

[11] Similar to this distinction between figurative and operative knowledge is Anderson's (1983) distinction between declarative and procedural knowledge (see also Pascual-Leone, 1995).

Of course, both figurative and operative schemes may be found at any level of abstraction and within any modality.

Certain schemes, as previously mentioned, are organized according to a temporal sequence and include an ending component. When a scheme contains a representation of time, it is called a *fluent*, a term taken from artificial intelligence. In figurative fluents, the time representation appears as an expectation (that a state x is followed by a state y, and finally a state z, etc.). In operative fluents, representation of time could appear in the form of a temporally sequenced series of operations, parts of a procedure, or steps of a program.

Executive schemes are an important subclass of operative fluents, involved in the plans and control functions of the mind. *Plans* are operative fluents that represent procedures or procedure segments, strategic moves, and sequences of steps that a person's behavior or thoughts might follow. Executive schemes with *control* functions do the work of monitoring mental activity, which is, using and regulating an organism's attentional resources, verifying that those schemes necessary for a plan's execution are active in each moment. In this way, the executive schemes regulate the combination and the temporal order of schemes activated to attain a purpose or to put into action a strategy (Pascual-Leone, 1976a; Pascual-Leone et al., 1978). Thus, one sees that executive schemes can be quite sophisticated, especially in an educated adult.[12] However, even a young child will already have developed its first executive schemes, though they will be rudimentary and based only on analogical representations, for example, plans for exploring objects and the environment.[13]

Examples

A few illustrative examples may provide a clearer sense of this threefold system for classifying schemes. The mental representation of how to tighten a screw would be an operative scheme at the zero level in the motor modality. The mental representation of the verb "go" is an operative fluent at the zero level in the linguistic modality. In the case of a person for whom the rules for solving an algebraic system with two unknowns were well

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[12] Contrary to theories that posit one central executive system (e.g., Baddeley, 1986), the TCO postulates a great multiplicity of specialized executive schemes.

[13] The first, simple executives would be developed between 1½ to 2 years of age (e.g., Pascual-Leone, 1996). For instance, they could organize a sequence of actions in symbolic play, a plan for producing a two-word sentence, or the invention of new means to a certain goal. Pascual-Leone and Johnson (1999), however, adopt a different terminology and call "executive" practically any coordination of sensory-motor schemes, even at the age of 6 months. We believe, however, that this difference is only due to an attempt at simplifying language in the latter chapter and that the actual claim made by the TCO is that executives appear late in the second year of life.

learned, the mental representation of this set of rules would be an operative scheme in the conceptual-propositional modality. The scheme's level would be superordinate with respect to the variables and the individual rules. The scheme that allows one to recognize a rose would be a figurative scheme at the zero level in the visual modality. The mental image of a rose would itself be composed of subordinate level schemes that are also figurative and in the analogical modality. Activation of these schemes representing various parts of the rose would require some mental effort. An example of a figurative fluent (in the analogical-conceptual modality) might be the *frame* that generically represents the "Hollywood comedy": a set of prototypical roles, characters and interactions within which the developments of each scene carry more or less detailed expectations for the following scenes.

Clearly, individuals develop their own repertoire of schemes different from that of any other person. In the TCO, schemes are also referred to as *subjective operators*: "operators" in the sense that when applied to a particular mental state (a perceptual input or other previously activated schemes) they produce a new mental state; "subjective" in the sense that they are specific to every individual and that the process of their successive activation constitutes the content of one's subjective experience. It is the experiences that individuals have in their own environments that allow the formation and coordination of schemes. For example, the concept of orthogonal projection or the procedure for making coffee are unitary schemes only for those persons having sufficient experience with orthogonal projection or making coffee. For the inexpert, to discriminate an orthogonal projection from other types of drawings or to prepare coffee would require the coordination of several schemes.

Although having stimulated little specific research, the TCO system of classifying schemes has a theoretical importance as a guide in construction of models concerned with identifying the schemes involved in a task or mental activity.

SECOND-LEVEL OPERATORS

Another fundamental construct in the Theory of Constructive Operators is that of second-level or *metasubjective operators*. The TCO treats schemes of the first level as "subjective" operators, in part because every individual possesses a large personal repertoire of these. Even though a person is not aware of which individual schemes are active in one's mind, it is the activation of sets of schemes that determines the content of subjective experience. Metasubjective operators, instead, cannot be a part of subjective experience because, unlike schemes, they do not have their own information content. These second-level operators are information processing mechanisms that act on the first level operators (i.e., schemes). Also in contrast to the subjective operators, those of the second-level constitute a small number of general resources common to all people. Although there are quantitative differences among people in the strength or efficiency of the metasubjective operators, there are no qualitative differences in the repertoire. It would be impossible for a person to have a metasubjective operator not possessed by others.

Metasubjective operators serve the function of increasing or decreasing the activation levels of schemes, and they enable the formation of new schemes. As just stated, when a scheme is activated it tends, in turn, to activate other compatible schemes and to inhibit incompatible ones. However, if a scheme's activation level depended solely on the perceptual input and on the activation or inhibition received from other schemes, then in each moment we would be prisoners of our current repertoire of schemes, of the greater or lesser salience of the stimuli, and of the propagation of activation among the schemes most closely connected to one another. Thus, it is necessary to posit the existence of other mechanisms distinct from the schemes that enable processing and integration of information, so that one can go beyond the information given and beyond the current scheme repertoire. One of these mechanisms, called "central computing space" in early writings, has already been mentioned in the section entitled "Schemes and Processing Capacity." Here we describe the metasubjective operators included in the theory, though we also note that it is certainly possible to hypothesize other operators or to discover that the functions now attributed to a single mechanism depend instead on two or three different ones. In such cases, of course, the theory would have to be modified.

Learning Effects

The psychological mechanisms that enable the development of new schemes, that is, the *C, LC* and *LM operators*, have been inferred from numerous Piagetian, cognitive and behaviorist studies of learning.

The *C operator* (for *C*ontent learning) corresponds to Piaget's accommodation of schemes (Pascual-Leone & Goodman, 1979). Accommodation occurs when one's experience violates one's expectations; that is, when a scheme *x* is strongly activated in a situation, but *x* leads to the activation of some schemes that are incompatible with other ones activated in that situation.[14] At that point, the repertoire of schemes can be enriched by the

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[14] For example, a plastic apple might activate schemes for grasping and biting, but one's tactile experience will activate other schemes incompatible with biting. In this way, from the scheme that represents apples one could differentiate a scheme that represents artificial apples, that is, something with the appearance of an apple that does not, however, lend itself to being eaten.

formation of a new scheme *x* that is similar to the one already strongly activated but different in some feature. In addition to Piagetian accommodation, the *C* operator mechanism for forming schemes also seeks to explain discriminative learning as described by behaviorists.

ED: x' prime? see msp 21

The two *L* operators (for structural *L*earning) provide an account of other types of learning that involve the formation of a superordinate scheme. In these cases the formation of the new scheme derives not from the modification of an existing scheme, but from the coordination of two or more schemes activated simultaneously (Pascual-Leone, 1976a, 1976b; Pascual-Leone & Goodman, 1979). The activation of any one of the schemes coordinated within the superordinate scheme would automatically result in the activation of all the others. The phenomenon of automatization of cognitive processes provides a notable example of the coordination of schemes.

The *L* operators are labelled *LC* and *LM*. The *LC* operator involves slow, gradual learning processes based on the frequent coactivation in a given context of two or more schemes already formed by means of the *C* operator. Complex schemes are the result, and they are often analogical representations of experiential content that are not readily transferable beyond the context in which they were acquired. Nevertheless, they make up a dense associative network (that could produce interference effects if one had to activate only one of the component schemes).

LM learning, on the other hand, is rapid and abrupt. It is produced with the use of attentional resources (see the *M* operator in the following section), sometimes with conscious learning strategies. It leads to structures that are hierarchically organized and do not include a representation of the context in which they are learned (hence, it is sometimes called logical-structural learning), and thus are less susceptible to interference. *LM* learning could produce representations of various sorts, from concepts to complex procedures or symbolic rules. Although the *LC* and *LM* distinction has important theoretical and practical consequences (Pascual-Leone, 1976a, 1995; Pascual-Leone & Goodman, 1979; Pascual-Leone & Johnson, 1999), it is not essential for most of the matters we consider in this book, and we often speak simply of the *L* operator.

The work of Miller and his colleagues (Miller, Bentley & Pascual-Leone, 1989; Miller, Pascual-Leone, Campbell, & Juckes, 1989) is important to illustrate learning of executives. These authors have repeatedly administered the CSVI and other measures of the central computing space to low socioeconomic level African (Zulu) children. In a control condition, in which attentional strategies had little importance because of lengthy duration of the stimulus and a prohibition on responding prior to its discontinuation, they showed that the capacity of these children was equivalent of Canadian children participating in other studies. On tests for which success also depended on adequate executive schemes (e.g., schemes for controlling attention in a tachistoscopic version of the CSVI), performance by Zulu children on the *first presentation* was inferior to that of Canadian children of the same age. However, on *successive presentations* of parallel forms of these tests, the same children obtained higher scores. Miller and colleagues attribute the improved results to the formation and partial automatization, while performing the tests, of appropriate executive schemes. Bentley, Kvalsig, and Miller (1990) reached the same conclusion in a similar experiment with a different type of test (the FIT; see chap. 9).

Attentional Energy

The *M* operator (for *M*ental energy), also metaphorically called "central computing space,"[15] has the function of incrementing activation of schemes that are relevant to a task, but that are not sufficiently activated by the perceptual input or by other operators. Thus, the *M* operator is an attentional resource, similar to Kahneman's (1973) well-known energetic model of attention. But, in contrast to Kahneman's theory, the TCO specifies the *M* operator's capacity in quantitative terms, expressing it as the maximum number of schemes that the *M* operator could activate simultaneously.

Pascual-Leone (1974, 1980, 1987; Pascual-Leone & Johnson, 2005) suggests a possible neuropsychological base for the *M* operator. He views the executive schemes, localized in the frontal and prefrontal lobes, as utilizing the energy resources of the reticular system to activate schemes localized in other cortical areas; and he suggests that the increase with age of the *M* operator's capacity is due to the maturation of the neuronal structures on which it depends. Maturation, and therefore the increase in the available reserve of mental energy, would be a continuous phenomenon with increasing age; however, the discontinuous, stage-like aspects of mental development would be due to "qualitative leaps" that occur every time that the increase in energy is sufficient to activate one more scheme.

Many studies, including those on the CSVI just cited, support the hypothesis of an increase in the capacity of the *M* operator (or *M* capacity) of one scheme every 2 years, from 3 to 15 years of age. Pascual-Leone and Johnson (1991) extend the study of the *M* operator's development to the first years of life, considering experiments with linguistic tasks (Benson, 1989) and memory tasks (Alp, 1988, 1991; Benson, 1989) in addition to the Piagetian literature. They maintain that less mental energy is required to activate a sensorimotor scheme than to activate a scheme at the symbolic representation level; and they suggest that the number of sensorimotor schemes that

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[15] The expression "central computing space" has often misled readers to believe that the *M* operator functions like a short term memory similar to the one hypothesized by Atkinson and Shiffrin (1968). In order to avoid this misinterpretation, this metaphoric term has fallen a bit into disuse.

the *M* operator can activate simultaneously increases from one at the age of about 1 month to seven at about 3 years (for further discussion of the development of *M* capacity in the sensorimotor period, see Pascual-Leone & Johnson, 1999).

In a chapter on aging, Pascual-Leone (1983) suggests that the available capacity of mental energy declines with advancing age and that, on average, 60-year-olds have at their disposal an *M* operator functionally equivalent to that of children in the 11–12-year-old range (see Morra, Vigliocco, & Penello, 2001, for new supporting evidence).

M capacity is expressed by the formula $e + k$, in which e represents the executive schemes and k the number of operative and figurative schemes that can be activated simultaneously. The suggestion is that the amount of energy necessary for activation of the executive schemes is modest, given that these are well-learned operations and control processes. Moreover, it is assumed that the quantity of mental energy required to activate executive schemes is approximately equivalent to the *M* capacity of a 2-year-old child (Pascual-Leone & Goodman, 1979), this is why executive schemes begin to appear around 2 years of age. For these reasons, e is treated as a constant in the expression of the *M* capacity for children of 3 years and older.[16] Of course, an adult's executive schemes are more complex than those available to a young child, but this aspect of development is attributed to learning and automatization. Execution of the complex operations provided for by adult executive schemes requires holding several items of information in mind, but it is to these items that the *M* operator must dedicate most of its resources (i.e., those represented by the k parameter). Table 2.1 summarizes the maturation of *M* capacity according to this theory.

The Inhibition of Irrelevant Information

The *I operator* (for *I*nterrupt) carries out functions complementary to the *M* operator; it is a central attentional mechanism that inhibits (disactivates) irrelevant schemes in a top-down way. It may be easiest to see its role in the context of selective attention.

Consider, for example, the Stroop effect (Mac Leod, 1991; Stroop, 1935), which involves stimuli that have mutually contradictory properties. Adults are able to read the name of a color, for example the word "red," more quickly than they are able to respond "red" when presented with a figure of this color. And when presented with the names of colors written in different

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[16] In older children and adults, executives (i.e., plans and controls) would monitor task performance and regulate allocation of *M* capacity to content schemes. In infants, who still lack appropriate executives, task performance would be motivated by either a need or a nonmediated affect, which triggers the arousal necessary to mobilize *M* energy that activates one or more sensorimotor schemes.

TABLE 2.1
Development of the Capacity of the *M* Operator According to the TCO

	M Capacity	
Age	e	$e + k$
0–1 month	0	
1–4 months	1	
4–8 months	2	
8–12 months	3	
12–18 months	4	
18–26 months	5	
26 months–3 years	6	
3–5 years	7?	$e + 1$
5–7 years		$e + 2$
7–9 years		$e + 3$
9–11 years		$e + 4$
11–13 years		$e + 5$
13–15 years		$e + 6$
15 years–adult		$e + 7$
after 35–40 years		in decline

Note. The ages indicated are approximate values and relative to the population average. Certainly individual differences exist related to early or late maturation. The figure "7?" in the e column indicates that how *M* Capacity grows in terms of sensorimotor tasks after 3 years of age is not clearly determined.

colors, for example the word "red" written in yellow, they do not find it particularly difficult to read the word. However, they do demonstrate difficulties (slower answers and occasional errors) in stating the color in which such words are written. Being overlearned and more accessible, the information about the word's meaning interferes with the use of the incompatible information about its color. The fact that, nevertheless, one almost always succeeds in answering correctly suggests the existence of a process that discards the incorrect information.

The *negative priming* paradigm (e.g., Houghton & Tipper, 1994; Tipper, 2001) is another case that suggests the existence of an *I* operator. We have mentioned that the Stroop effect involves a delayed response to a stimulus because of irrelevant features of that stimulus, which must be inhibited. By contrast, negative priming involves a delayed response to a stimulus because of irrelevant features of a preceding one, features that in the current stimulus are present and relevant. A widely accepted interpretation of negative priming is that, after having inhibited a representation of an irrelevant aspect of the first stimulus, longer time is required to activate it when it becomes relevant for responding to the stimulus that follows (see Tipper, 2001, for a discussion).

Experimental research on inhibitory control processes has gained increasing importance, and several other paradigms have also been used both with adults (e.g., Friedman & Miyake, 2004; Mitchell, Macrae & Gilchrist, 2002) and in the course of development (e.g., Christ, White, Mandernach, & Keys, 2001; Wolfe & Bell, 2004).

Neuropsychology also indicates the existence of inhibitory cognitive mechanisms (e.g., Shallice, 1988). Patients with frontal lesions tend toward perseveration (they are unable to efficiently interrupt ongoing mental activities and processes), are easily distractible and have difficulty when it is necessary to ignore salient information. Brain imaging studies suggest that maturation of the frontal lobes is involved in acquisition of inhibitory control (e.g., Durston et al., 2002).

Pascual-Leone (1983, 1984; Pascual-Leone et al., 1978) suggests that inhibition of irrelevant information plays a role in many cognitive activities, including Piagetian problems and field-independence tasks. The reason is that these situations often require not only that one attend to relevant information, but also that one not be deceived by perceptually salient features or by well learned (but misleading) rules.

Pascual-Leone (1984; see also Dempster, 1992) hypothesizes that a central inhibitory mechanism is involved in selective attention, in Piagetian problems, in field dependence tasks, and in the control of those behaviors found lacking in frontal patients. Moreover, Pascual-Leone et al. (1978) maintain that in certain situations such as free recall or divergent thinking, for which an easy and rapid succession of ideas is valuable, one's performance depends on executive control schemes—*interruption and dis-interruption controls*—that regulate the activity of the *I* operator. Because the *I* and *M* operators act in synergy, their development might be intertwined in some way also (Pascual-Leone & Johnson, 2005). Besides controlled inhibition, automatic inhibition would also occur following each allocation of *M* capacity, to suppress activation of those schemes that are not under the focus of attention (e.g., Pascual-Leone, 1984, 1987, 1997).

Although these hypotheses are suggestive, it must be recognized that within the TCO the properties and functioning of the *I* operator are not yet completely formalized. Among the important claims are that the *I* and *M* operators are co-functional, as they are both under the control of executive schemes localized in the frontal and prefrontal lobes; that they both develop during infancy and decline in advanced age; and that in both of them there are individual differences (i.e., inhibitory processes are less efficient in field-dependent individuals). A further specification of the *I* operator's properties would constitute an important development of the theory. Some empirical evidence supports these views (see the section entitled "Research on Inhibitory Processes" for examples) and, at the same time, opens the way to further refinements.

Field Effects

The *F operator* (for *F*ield) represents field effects in information processing. Such effects can influence the activation of figurative schemes (in perception, this is the case of the Gestalt laws, that is, the principles of closure, proximity, similarity, symmetry, etc.; see Kanizsa, 1979). Field effects can also influence the activation of operative schemes (e.g., the attentional phenomenon of spatial stimulus–response compatibility: a task is facilitated if the organization of responses is congruent with that of the stimuli).[17]

Expressed in intuitive terms, the function of the *F* operator is to facilitate the activation of the simplest possible representation of the stimulus configuration. However, as Pascual-Leone recognizes, it is not easy to formalize the concept "simple representation of a configuration" and thereby express in a precise, yet comprehensive way the role of the *F* operator in cognitive processes. The problem remains open notwithstanding the frequent informal use of similar concepts by psychologists of all orientations, and some valuable attempts to specify models of them (e.g., Hochberg, 1988; Kornblum, Hasbroucq, & Osman, 1990).

According to Pascual-Leone (1976b, 1980) one tends to assimilate the conceptual structure of a problem to its perceptual structure. The *F* operator is the organism's tendency to simplify the pattern of activated figurative schemes, and to structure its operative processes in such a way as to make them congruent with this simplified organization of the figurative schemes.[18]

This informal, but intuitively clear, definition can be illustrated with respect to some Piagetian problems.[19] For example, Inhelder et al. (1974) presented children with a zig-zag line constructed from sticks and asked them to construct from other sticks a straight line of the same length as the model. The global configuration of the model led the children to consider the start and end points of the line rather than the number or length of the sticks from which it was composed. They tended, therefore, to construct a straight line with its start and finish aligned side by side with those of the model line. Although such a line is clearly shorter and constitutes an incorrect solution, it is nonetheless a solution that satisfies the *F* operator's requirement of simplicity (Pascual-Leone, 1976b).

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[17] Even in such a simple task as discrimination of whether a stimulus appears in a higher or lower position, one performs better if the response involves pushing buttons that are placed higher and lower, respectively, rather than in other arbitrary positions.

[18] Pascual-Leone and Johnson (1999, p. 181) further specify that this operator "minimizes the number of schemes that directly apply to inform the performance (including perception or representation) . . . while maximizing the set of distinctive, salient features of experience (activated low-level schemes)."

[19] Piaget and Inhelder (1959, 1966) list a "figural factor" among the causes of the horizontal *décalages* that have the ability to interfere with or facilitate operative thought. However, within the framework of Piagetian theory such a factor has never been studied thoroughly.

This same factor can also induce incorrect judgments in the conservation problems (Pascual-Leone, 1980). For example, in a conservation of volume problem, asked which object's immersion will result in the greatest rise of the water level, children tend to predict a rise based on the height of the object itself.

The *F* operator can induce incorrect judgments not only in problems in which perception plays a role, but also in problems of a purely symbolic nature. When asked to produce all possible permutations of a set of symbols, naïve participants (who are unfamiliar with the mathematical concept of permutation) produce responses that appear different from one another, rather than following a systematic approach (de Ribaupierre, 1989). Also in the four-card problem described in chapter 1, people's tendency to choose (incorrectly) the cards with the explicitly mentioned symbol seems to be a case of responding in a manner compatible with the stimulus configuration.

In the cases considered thus far, the *F* operator induces formulation of incorrect or inappropriate judgments. As the reader may have already realized, the *F* and the *I* operators may act in a reciprocal antagonism. Problematic situations are problematic because the solution that seems most obvious and intuitive is, in fact, wrong. But this doesn't mean that the *F* operator is always, or even generally, misleading. On the contrary, in most everyday circumstances it is useful for producing judgments that are consistent with the structure of the surrounding world. Often, for example, a judgment based on salient perceptual characteristics is effective and more economical than an accurate assessment. The *F* operator also plays a facilitating role in abstract or symbolic tasks provided that they are constructed in such a way that the correct answer is congruent with the emergent structure of the stimuli. Pascual-Leone (1980) suggests that conditions for Piagetian equilibration processes are optimal when the simplest synthesis of the information activated by a problem constitutes a correct solution.

Automatic Encoding of Space and Time

The *S* operator (for *S*pace) is composed of the cognitive mechanisms that compute the location of objects in the physical environment and the spatial relations among them; neuropsychologists call it the "where" system and locate it in the dorsal-parietal pathway. Its does not carry out a conscious calculation, but rather, there are automatic parallel processes involving information on spatial positions[20] (Pascual-Leone & Johnson, 1999, 2005). Possibly, acquisition of basic spatial concepts, such as the horizontal and vertical coordinates, may also involve *S* operator processes.

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[20] There is a debate about what spatial information is automatically encoded also in memory and what is not (e.g., Farrell & Robertson, 1998; Schumann-Hengsteler, 1992; Walker, Hitch, Doyle, & Porter, 1994). Neo-Piagetian theories could benefit from that debate in order to specify which aspects of spatial information processing tax limited attentional resources.

In addition, Pascual-Leone hypothesizes the existence of a *T* operator (for *T*ime): not a conceptual representation of time but a process of automatic encoding of real time. It would be involved in automatic structuring of currently evolving states of experience and in episodic memory encoding (and therefore also in the construction of the self), but also in the acquisition and use of the sequential structures of language, in the acquisition of rhythms, in learning expectancies about objects, and in structuring simple executive plans and strategies. Also the literature on the "psychological moment" of the first half of the 20th century could be interpreted in this light. The conjectures on the *T* operator (e.g., Pascual-Leone & Johnson, 1999), however, still require further development.

Emotion-Based Activation

The *A* operator (for *A*ffect) represents emotion-based contributions to the activation of schemes. As described previously, the Theory of Constructive Operators posits specific *affective schemes* that embody the physiological components and motivational effects of emotions, and *personality schemes* that coordinate affective with cognitive schemes. One possible consequence of the activation of affective schemes is the temporary flow into the cognitive system of a quantity of energy capable to activate a certain number of cognitive schemes beyond those already activated from other sources. In certain cases, this activation might favor better performance (e.g., Miall, 1989, discusses the role of affect in the comprehension of literary texts); in other cases the activated schemes might be irrelevant or involve strategies incompatible with rational performance (e.g., in panic the representation of a target is so strongly activated that it may inhibit representation of alternative routes). The *A* operator is particularly important during infancy, when the *M* operator and other endogenous sources of scheme activation are still rather weak.

THE TCO AND TASK ANALYSIS

Up to this point we have considered in detail the various constructs of the Theory of Constructive Operators. Let us turn now to a consideration of the overall picture they form.

General Characteristics of the TCO

The TCO is a complex theory that proposes a clear distinction between two levels of constructs, namely the subjective operators and the metasubjective operators. One of the purposes of the TCO is to account for *cognitive* *conflicts*. The theory posits that the knowledge and strategic processes activated in a situation are multiple, and possibly contradictory; and further, that in such cases, various metasubjective operators favor the activation of one or another set of schemes.

The TCO also provides a coherent approach to *cognitive styles.* According to Pascual-Leone (1974, 1989; see also de Ribaupierre, 1989; Globerson, 1989; Pascual-Leone & Goodman, 1979) cognitive styles derive from different balances among the mental operators that act in contrast with one another. For example, he suggests that in field-dependent individuals the *F, L*, and *C* operators tend to prevail over the *I* and *M* operators (and over the executive schemes that control them) and that the opposite holds for field-independent individuals. Thus, the difference among persons of various types is not a deficiency or difference with respect to a single variable, but rather is a matter of a different balance among numerous variables.

Extensive research (e.g., Baillargeon, Pascual-Leone, & Roncadin, 1998; Case & Globerson, 1974; Globerson, 1983a, 1983b, 1985, 1987, 1989; Goode, Goddard & Pascual-Leone, 2002; see also Pulos, 1997, and related commentaries) shows that field independence and *M* capacity are different constructs, and that field-dependent persons need not have lesser *M* capacity than field-independent ones. Rather, the two cognitive styles differ in terms of processing strategies, perceptual biases, or allocation of attention, such that performance turns out to be different on some measures of *M* capacity or working memory as well.

The TCO also suggests a solution to the *learning paradox* (e.g., Juckes, 1991). Pascual-Leone criticizes theories in which one's new and creative performances (such as succeeding for the first time in one's life in solving a conservation problem) are explained by the acquisition of logical competencies, inference rules, production systems (Klahr & Wallace, 1976) or other specific knowledge that is transferable to new problems. If such explanations were correct, it would be necessary to ask how one had acquired these logical competencies or other specific knowledge that had never before been demonstrated or used. Could learning without experience be possible? Bereiter (1985) expresses the learning paradox as follows: according to some theories, in order to acquire a new ability or piece of knowledge an individual must already implicitly possess a cognitive structure at least equal in complexity to that of the new acquisition, but this requirement is paradoxical.

There are two possibilities for resolving the paradox. One approach is to avoid a need for learning experiences by adopting (like Beilin, 1971) an extreme innateness hypothesis, a possibility that is coherent but not very plausible. The other assumes, like Pascual-Leone (1980), that creative and novel performances do not depend on preexisting knowledge alone, but also on the intervention of general mechanisms (the metasubjective operators). For example, in the case of solving a conservation problem, the *M* operator and the *I* operator are certainly involved: *M* to activate relevant knowledge and *I* to inhibit the tendency to respond on the basis of a salient dimension. Also involved is the *F* operator that releases a simple representation and a response that is consistent with the activated knowledge. In this case, the participation of the *M* and *F* operators constitutes the process that Piaget calls *equilibration*. By means of these new or creative performances one could also learn specific knowledge, competencies, or rules that are transferable, though only subsequently, to similar situations or problems. Thus, the metasubjective operators hypothesis provides a resolution of the paradox of acquiring knowledge without prior experience (which would be equivalent to saying: knowledge learned without having learned it).

Finally, the TCO makes an important contribution to task analysis, that is, to the identification of all the knowledge and abilities required for successful execution of a task.

Task Analysis

The TCO is a complex and multifaceted theory, and its approach to *task analysis* and to the formulation of processing models for specific situations reflects its complex, articulated form. From the point of view of the TCO, task analysis requires the psychologist to perform the following operations:

1. Identify the strategies, or the various strategies (also the incorrect ones) that one can implement in a given task. If more than one strategy is identified, then identify also the factors that might lead an individual to follow one strategy rather than another (e.g., metasubjective factors, experimental or situational variables, or prior experience).
2. Describe the temporal unfolding of each strategy analyzed, decomposing it in a sequence of operations or successive steps.
3. Specify the set of schemes that are activated[21] in order to carry out each of the described steps.
4. Indicate the causes of each scheme's activation; that is, whether it is activated by perceptual input or by one or more subjective operators.

These four points, however, describe the final result of a task analysis, not how the task analysis is conducted. The latter is discussed in chapter 9.

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[21] The theory posits hierarchies of schemes in which those schemes that are more complex have less complex ones as components. In a task analysis it is appropriate to list the highest level activated schemes, because in this way the activation of the components of the superordinate schemes is also granted.

Task analysis is theory guided and affords various inferences and predictions. For example, if one concludes that in order to implement a certain strategy a person must activate five schemes by means of the *M* operator, then one can predict that children with an *M* capacity less than $e + 5$ will not be able to carry out the strategy and that attempts to do so will lead to imprecise and inadequate outcomes. Or suppose an analysis recognizes two alternative strategies, one of which is facilitated by the *F* operator whereas the other employs the *I* operator; then one could predict that the first strategy is more likely to be adopted by field-dependent individuals whereas the second is more likely among field-independent individuals. Or if, in an experiment or instructional situation, certain linguistic or perceptual variables are manipulated in such a way as to increase or decrease the salience of some aspect of a problem, this manipulation could increase the probability of particular schemes being activated without any intervention of the *M* operator. The task is thus facilitated and becomes performable by a person with an *M* capacity smaller (by a quantifiable amount) than that required for the standard version of the task. Finally, if one introduces learning phases that automatize the activation of a scheme or coordinate previously separated schemes, the *L* operator will replace or cooperate with the *M* operator, thereby facilitating the task to a degree corresponding to the number of schemes involved.

One may note that task analysis permits both qualitative and quantitative predictions. Qualitative examples include predictions on the effects of information salience, or the relations between cognitive style and performance. Quantitative ones include predictions regarding the *M* capacity required to follow a given strategy, or the degree of task facilitation that occurs when one is able to specify the schemes activated as a result of manipulating particular variables. In some cases, particularly precise quantitative predictions have been made; for example, for performance in a memory task (Burtis, 1982, exp. 1) or for school-age children's planning of their drawings (Morra, Moizo, & Scopesi, 1988).

Either for practical reasons or simply due to excessive difficulty, it is not always possible to carry out a detailed analysis of all the aspects of a task. For example, the temporal breakdown of a strategy into successive steps might be uncertain, and for this reason the psychologist might be limited to analyzing one or two of its crucial moments. As another example, there might be doubts about the sources of activation for certain schemes and these would limit a psychologist to approximate evaluations. In both of these cases, predictions and inferences would be less accurate.

We turn now to describing some of the research carried out within the TCO framework that provides examples of task analysis and of the methods used to test the predictions based on this theory.

A CLASSICAL PIAGETIAN PROBLEM: THE CONTROL OF VARIABLES

A problem studied by Inhelder and Piaget (1955), variously translated from the French as "dissociation of factors," "separation of variables," or "control of variables," involves determining the variables that influence the flexibility of a rod. Several rods are laid out horizontally and fixed at one end. The rods vary in terms of material (wood, brass, steel), length, cross-sectional form (round, square) and thickness; and dolls of different weights are placed on the free end of each rod. A basin of water lying beneath the free end allows a practical evaluation of the flexibility concept in terms of whether the rod approaches or touches the water. This simple situation reveals the children's ability to determine the individual dimensions along which the rods vary as well as their ability to use a basic principle of experimental method, namely varying one factor at a time while holding all the others constant.

Up to about 6 years of age, Inhelder and Piaget found prelogical performance; between 7 and 11 years they found an increasing ability to classify the observed facts, but without any systematic approach; and only in the oldest children did they find an ability to vary all the factors independently (still with some uncertainty up to 14 years). According to the authors, the task is certainly a formal operations one as it requires a propositional reasoning that involves implication and a systematic combinatorial calculus.

Task Analysis

Case (1974a) made the prediction, counterintuitive at the time of the research, which the scheme for control of variables could be made accessible to 8-year-olds. We now review the essential features of his analysis.

According to Case, a child whose repertoire includes the appropriate executive scheme would be able to adopt a systematic comparison strategy. Thus the child would be able to verify whether a rod with a certain characteristic bends more than another that does not have the characteristic while simultaneously making sure that the rods do not differ with respect to any of the other characteristics.

This demanding operation requires that four schemes be activated. Suppose, for example, that a child has noted that one of the long rods bends more than one of the short ones, and seeks to verify whether longer rods are more flexible in general. The schemes that are *simultaneously* involved are: (1) a figurative scheme representing the observation that the long rod bends more; (2) an operative scheme corresponding to the rule "if there is also some difference between the rods other than length, mark it"; (3) a figurative scheme representing a relevant property (for example, the thickness) of rod A; and (4) a figurative scheme representing the corresponding property of rod B. To carry out this check the child must alternately direct attention to rods A and B, and for these rods *one* of the schemes indicated by (3) and (4) would be activated, in turn, by perceptual input. The operation would then be repeated for each of the relevant variables.

If this strategy requires simultaneous activation of four schemes, one of which is activated by the input, then it is possible to conclude that the required M capacity is $e + 3$. Therefore, the normal child of 7–8 years should be able to implement it. According to Case, the reason why success is not usually attained before 11 years is that younger children do not possess adequate executive schemes relating to the concept of "rigorous proof," a concept for which occasions to acquire it are rare. Nevertheless, according to Case, acquisition of such a concept is possible with an M capacity of $e + 3$; and therefore, it should be possible to teach it to 8-year-olds who meet the following conditions:

1. they are cognitively normal, and in particular they have acquired the M capacity typical of their age;
2. they are given the opportunity to learn the concept of rigorous proof; and
3. they have at least a minimal degree of field independence.

Experiment

To test this analysis, Case (1974a) selects 6 groups of children, three of which are trained with respect to the rigorous proof concept whereas the other three act as control groups. In each condition (training and control) there are: a group of 8-year-old field-independent children, a group of 8-year-old field-dependent children, and a group of 6-year-old field-independent children.

Beginning with the demonstration of a nonrigorous proof, the experimental groups receive instruction that is systematically guided toward understanding the concept of interest. They are asked to compare an aluminum rod inserted in a black block (in which a weight is hidden) with a brass rod inserted in a white block and to decide whether the aluminum or brass rod weighs more. The deception is then revealed and the researcher demonstrates that the proof should be carried out by comparing two rods within equivalent blocks. The training continues with different tasks and materials, alternating explicit explanations and invitations to explore, verbal questions and practical experience.

Subsequently all the children, both from the training groups and the control groups, undertake criterion tasks (the control of variables) both with Piagetian materials (the flexible rods) and with another kind of stimuli.

Among the 8-year-olds, those who are field-independent and are trained produce, as predicted, a higher number of correct responses. Comparing the four groups of 8-year-olds one sees that *both* instruction *and* field independence yield significant effects. Trained or not, the 6-year-olds perform poorly on the criterion task. This result is also consistent with the theoretical predictions: the task analysis indicates, in fact, that the 6-year-olds are not yet endowed with the *M* capacity that is necessary in order to take advantage of the training.

Case concludes that Piagetian structural analysis, in terms of formal operations, can not explain the results of his experiment, but that the neo-Piagetian, functional approach does yield a satisfactory analysis.

IS THE WATER LEVEL HORIZONTAL?

The TCO has also contributed to the analysis of another classical Piagetian problem, the representation of water level (Piaget & Inhelder, 1947). The child is asked to indicate on a real bottle, or to draw on paper the level that water would assume if an empty bottle was refilled about halfway. The bottles are presented in various positions: upright, upside down, placed horizontally on a side, or tilted at various angles.

Piaget and Inhelder describe errors of various types (see also Fig. 2.1). Up to 3–4 years of age, children succeed only in indicating the presence of water in the bottle, for example with a scribble inside the bottle outline. Most 5-year-olds can represent the water level with a line, but they draw it parallel to the bottom of the bottle irrespective of its position, as though the water remained attached to the bottom. An advance is seen around 7 years: with sideways or capsized bottles the line is drawn horizontally, but with a tilted one the line is often drawn approximately parallel to the bottom. At age 9, with tilted bottles, in addition to correct horizontal responses some curious errors are also seen: lines inclined midway between the horizontal and parallel to the bottom, nearly vertical lines, and even some curved lines. Only at age 11–12 do Piaget and Inhelder find a majority of correct answers with inclined bottles. For a review of subsequent research, which also reports the frequency of errors at each age, see Pascual-Leone and Morra (1991).

Piaget and Inhelder (1947) explain the ability to represent water level by the development of spatial and geometric competence, in particular, the understanding of a system of horizontal and vertical coordinates. However,

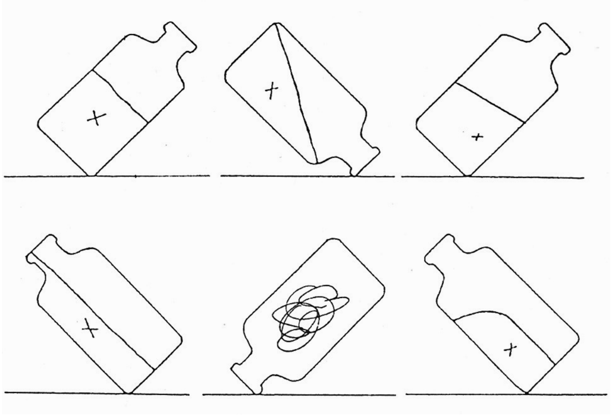

FIG. 2.1. Examples of errors on the water-level problem with tilted bottles. The child is asked to draw a line representing the water's level and to mark that portion of the bottle that contains water with an X. *Source:* Adapted from Pascual-Leone and Morra (1991).

ED: no ms for figures.

this account seems inadequate or incomplete given the occurrence of errors even in samples of adults, who have presumably already acquired the concepts of horizontal and vertical.

Task Analysis

Let's summarize Pascual-Leone's (1969) task analysis. The youngest children's responses are elementary because of their limited *M* capacity. They can activate simple executives related to instructions such as "imagine water in the bottle," "point with your finger" or "take a pencil and draw." With $M = e + 1$, however, they are able to activate only one symbolic scheme beyond the executive. For this reason they are typically limited to activating the figurative scheme for the concept of *inside*. The outcome is a gross gesture of pointing at any position in the bottle, or a scribble that indicates simply that the water is to be found in the bottle.

Acquisition around age 5 of the strategy of drawing the water parallel to the bottom is also a fruit of experience with bottles and other containers, which usually are positioned upright and thus tend to activate (*LC* operator) an image of water on the bottom of the container. The regular "good form" of this image makes likely (*F* operator) that the child accepts it as the correct answer. The strategy carried out at 5 years of age also demands an *M* capacity of $e + 2$; the two schemes required in addition to the executive are the mental representation of a *line* as a boundary of the water in the bottle and a representation of the *position* of the water, namely at the bottom.

Two reasons would account for the progress that occurs around 7 years of age. First, the acquisition of the scheme of water as a fluid (that falls and accumulates in the lower part of a container) seems necessary in order to overcome the earlier strategy of drawing water as if it adhered to the bottom. Second, the development of an M capacity of $e + 3$ makes it possible to activate, in addition to the executive schemes, three units of information: namely, the representation of a *line* (also required by the previous strategy), the scheme just described of water as a *fluid* that falls toward the lower part of a container, and the mental representation of the *position* of the water, that is, at least a rough assessment of which part of the bottle is lowest.

According to Pascual-Leone, however, an M capacity of $e + 4$, or in some cases even of $e + 5$, is necessary in order to respond correctly when the bottle is in a tilted position. Those children who don't yet have the necessary M capacity seek in imprecise ways, as suggested by the errors just described, to indicate that the water falls to the bottom. The five schemes that must be activated together include the same three required by the preceding strategy, and in addition, the mental representations of two points, one for each side of the bottle, positioned "equally low," that is, at the same height from the table or the support that holds the bottle. In connecting these points, one obtains a horizontal line under which one can draw the water. The children with more sophisticated physical and geometric knowledge, however, could succeed with an M capacity of $e + 4$ by activating the same three schemes required by the previous strategy plus a mental representation of the horizontal coordinate.

Although it is possible to achieve the correct solution by coactivating the four or five necessary schemes, there are, at the same time, important error factors that continue to influence even the responses of older children and of adults (especially field-dependent individuals lacking adequate physical knowledge). The F operator, in particular, induces errors in persons of every age, both because of the "good form" of the (mental or graphic) representation of water at the bottom of the bottle, and also because the motor response most compatible with the presented stimuli consists of producing right angles with respect to the sides of the bottle, in other words a line parallel to the bottom.

Correlational and Experimental Research

Pascual-Leone (1969) reports, both for 9–10-year-olds and for adults, correlations between the water level task and tests of field dependence, as well as experimental research yielding outcomes consistent with the analysis just discussed. He also reports that, among field-dependent adults, one finds not only more errors than among the field-independent, but also a greater variability among each person's responses; that is, field-dependent adults often oscillate between correct and incorrect responses. Numerous studies confirm the relationship between field dependence and the water level task, and others (De Avila, Havassy, & Pascual-Leone, 1976; Pennings, 1991) show a relationship between M capacity and the water level problem. Furthermore, numerous studies provide evidence that physical knowledge also explains, at least in part, the variability in performance. This result is also consistent with the task analysis just presented.

Pascual-Leone and Morra (1991) provide a detailed review of research on the water level task and its relevance to neo-Piagetian models. For the sake of brevity we only mention here one experiment (Howard, 1978) with a method that is notable in this context. In contrast to many studies in which the participants must produce a motor response (such as to draw a line), Howard asks adults to evaluate whether the photographs presented (in which water is either horizontal or inclined at varying angles) are actual or artificial. Those who do not recall the principle of horizontality of liquids make numerous errors. But, although the typical error in the studies that require a motor response is to incline the water line in the same direction as the bottom, Howard reports that the average error is in the opposite direction, though only by a few degrees. We are able to conclude that even if the physical knowledge is important, in adults the error of representing the water as leaning in *the same direction* as the bottom is *not* due to lack of physical knowledge, but precisely to that which Howard's method has eliminated: a field effect, inherent in the production of a graphic or motor response.

A recent study with more than 300 participants aged 5–13 (Morra, in press) tests several predictions (explicitly stated by Pascual-Leone & Morra, 1991), on the roles of M capacity, field dependence, and physical knowledge in performing the water level task. All predictions are satisfied except one, that is, it turns out that with horizontal stimulus bottles the minimum M capacity necessary for drawing a horizontal line is not $e + 3$, but instead, $e + 2$. This discrepancy can be accounted for by suggesting a minor correction in the task analysis: with horizontal bottles one scheme, representing the straight line, may be boosted by the F operator and, therefore, does not need to be activated by the M operator. This is because the vertical bottom and the horizontal sides and neck create a perceptual field of horizontal and vertical straight lines that facilitates a horizontal motor response. All other predictions, concerning either group mean performance, or prevailing error patterns, or minimum M capacity necessary for correct performance, or individual differences in degrees of angular error are supported by the data.

It seems remarkable that the model of the water level problem proposed by Pascual-Leone (1969) stands the challenge of time so well and still gains direct or indirect support from research by many authors who in some cases have a different theoretical orientation. It is not possible to review here all studies of the other Piagetian tasks framed within the TCO; we only mention some research on concrete (Case, 1975a, 1977; Toussaint, 1976) and formal operations (de Ribaupierre, 1980; de Ribaupierre & Pascual-Leone, 1979; Scardamalia, 1977), and on social and moral cognition (Chapman, 1981; Stewart & Pascual-Leone, 1992).

A PSYCHOLINGUISTIC PROBLEM: THE COMPREHENSION OF METAPHORS

The two preceding sections consider tasks that Piaget himself studied extensively. The remainder of the chapter is devoted to themes and research paradigms that are innovative with respect to the Piagetian tradition.

Language is an important area to which the Geneva school has dedicated only a few studies (e.g., Piaget, 1923; Sinclair, 1967). Despite Piaget's interest (1968) in structuralist linguistic theories, his conviction that linguistic development is essentially a consequence of intellectual development (Piaget, 1954, 1970b) prevented his research group from investigating the development of linguistic ability as such.

Decades of psycholinguistic research have clearly demonstrated, however, the specificity of language development, to the point that until recently an approach to language development that also takes into account the influence of general aspects of cognitive development could be seen as unusual or dissonant (for a debate, see Johnson, Fabian & Pascual-Leone, 1989; Johnson & Pascual-Leone, 1989b; Karmiloff-Smith, 1989).

The point made by Johnson, Fabian, and Pascual-Leone (1989) is that language development not only depends on specific acquisitions, but is also constrained by general aspects of cognitive processing, that is, by the development of such components of the human information processing system as the second-level operators of the TCO. Johnson, Fabian, and Pascual-Leone (1989) study, in particular, the role of the *M, F* and *L* operators in the understanding and production of subordinate clauses between 5 and 12 years of age.

Here we consider the research on metaphor comprehension, a problem that has been analyzed in some detail within the TCO framework. A metaphor transfers the meaning of one or more words from its literal sense to a figurative sense. For example, the phrase "Our school is a paradise" does not mean that it is literally a place where the spirits of the departed gather, but rather that it has such pleasant features that one could compare it to paradise. Richards (1936) distinguishes two elements of metaphor, the tenor (the primary subject to which the rhetorical figure refers) and the vehicle[22] (the expression adopted as an instrument of figurative expression). Metaphor permits a creative use of language, but at the same time involves a wider degree of ambiguity than the usual use of terms based on denotative exactness. For example, consider Robert Frost's metaphor regarding the road "less traveled by": within it the reader can find *multiple* clues for its interpretation, some of which are mutually compatible and some, perhaps, which are pertinent to the context of the poetry in which the metaphor appears.

One should not be surprised to learn that the ability to comprehend metaphors is another subject of dispute among psychologists. Some maintain that this ability is acquired at a relative early age, others in preadolescence. In fact, as with other abilities, metaphor comprehension proves more or less difficult depending on variations in experimental method, and there is debate as to the methods most appropriate for assessing it. In addition, the causes that allow children acquisition of metaphor comprehension are debated. Some authors recognize a possible role for general cognitive ability, such as logical competence in the Piagetian sense; but usually the explanations make reference to specific linguistic or conceptual knowledge (see Johnson et al., 1989; Vosniadou, 1987).

Task Analysis

Johnson and Pascual-Leone (1989a) observe that few studies have examined in detail the interpretations that children give to metaphors. Often the responses are only categorized as right or wrong, but in this way metaphor is treated as though it were not by nature ambiguous, susceptible to multiple interpretations. According to these authors the ability to understand metaphors should not be considered in all-or-none terms; rather, the few studies that attend to the content of the responses suggest a gradual acquisition of the ability to provide interpretations less and less tied to the literal meaning of the vehicle. Johnson and Pascual-Leone's theoretical proposal considers five types or "developmental levels" of metaphor interpretation.

The first level simply consists of inappropriate responses that deny any meaning to the metaphorical expression, or that understand it in a literal sense, or that distort the interpretation in a nonmetaphorical way. For a metaphor such as "my sister was a mirror" the response "she was standing in front of a mirror" would be considered inadequate for these reasons.

The subsequent levels require an M capacity that increases in accordance with the connection to be found between the tenor and the vehicle.

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[22] For example, in the metaphor considered, "our school" is the tenor and "a paradise" is the vehicle.

The second level, called *identity*, requires an M capacity of $e + 3$ in that it involves the activation of a figurative scheme that represents the vehicle, another that represents the tenor, and an operative scheme for identifying identical aspects of the two objects. At this level, our example metaphor might be interpreted as "one could see oneself in her eyes." This interpretation is not a literal one; however, it is based on a shared property of mirrors and human pupils (the optical reflection of images) and does not involve any semantic transformation.

The third level, called *analogy*, involves the semantic transformation of some aspect or property of the vehicle. With the same metaphor, the response "my sister resembles me" is also based on a mirror's property of reproducing images but here is understood in two different senses: the optical reflection in the mirror and the similarity of the two siblings' faces. A person with an M capacity of $e + 4$, seizing on a possible identity (an aspect with respect to which the two objects might be equal) could produce an analogy by activating four schemes: three figurative ones corresponding to the tenor, the vehicle and the just-formed identity meaning, and an operative one to transform the first provisional interpretation, adapting it to the characteristics of the tenor.

The fourth level of responses is called *concrete experiential predicate*. It takes the form of a description of a prototype, an event or a concrete example regarding the tenor. This type of response also requires that one consider some property or aspect of the vehicle, but only as a clue to evoke pertinent aspects of the tenor. In the sister/mirror metaphor, the response "you were playing Simon Says and your sister would copy you" would be classified as a concrete experiential predicate.

The fifth level is called *generic conceptual predicate*. Also in this case the respondent's verbal expression must refer only to the tenor and not to the vehicle. In comparison to the fourth level, which involves an aspect or a concrete example of the tenor, responses at this level involve a more general or more abstract concept or property attributable to the tenor such as in, "my sister takes me as an example."

The responses classified as predicates presuppose that the respondent has identified an analogy that leads to the choice of properties of the tenor that allow reinterpretation of the analogy in a more elaborate way. The generic conceptual predicate requires an M capacity of $e + 5$ as it entails four figurative schemes (tenor, vehicle, the provisionally established meaning for the analogy, and at least one concept that is more abstract relative to the tenor), plus one operative scheme that changes the analogy in a way that is closely relevant to the tenor. The concrete experiential predicate could be formed in the same way, with the only difference being that in place of the abstract concept a figurative scheme is activated that represents some experiential knowledge of the tenor. At least occasionally even those with an *M* capacity of $e + 4$ can produce responses at this level in situations for which experiential knowledge is sufficiently well learned as to be activated by the *LC* operator rather than requiring attentional energy.

In short, an *M* capacity of $e + 3$ is required for identity, $e + 4$ for analogy, $e + 5$ or on occasion $e + 4$ for concrete experiential analogy, and $e + 5$ for generic conceptual predicate. Obviously one must also possess the necessary conceptual figurative schemes and linguistic operative schemes. Finally, Johnson and Pascual-Leone maintain that a metaphor is better interpreted and the *M* capacity required is reduced when the context (both linguistic and nonverbal) facilitates one's attention to relevant properties of the tenor.

Experimental and Correlational Research

In their primary experiment Johnson and Pascual-Leone (1989a) ask the participants (children from 6 to 13 years of age, plus an adult group) to give all the interpretations that come into mind for the six metaphors made up from the possible combinations of two tenors (my sister and my shirt) and three vehicles (a rock, a mirror, and a butterfly). For each metaphor, the highest level interpretation that each person is able to produce is noted. Each also completes an intelligence test with measures of both verbal and nonverbal reasoning, a verbal test of divergent thinking, and two nonverbal measures of *M* capacity: the figural intersection task (see chap. 9) and a variation of the CSVI.

The results conform to the predictions made on the basis of the task analysis. With 6-year-olds, inappropriate answers are most prevalent; at 7 years and above, the majority of responses can be classified at least as identity; from 9 years, at least half of the responses are analogies or predicates; and from 11 years, the majority of responses are classified as predicates. If instead of assessing the results from the point of view of age, one considers the growth of *M* capacity from $e + 2$ to $e + 5$, one observes just as clearly the predicted pattern of responses, There is a strong correlation between the ability to understand metaphors and performance on the measures of *M* capacity, even though these measures are nonverbal and do not share any content or specific knowledge with the metaphors.[23]

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[23] The correlation between *M* capacity and metaphor comprehension remains significant even with age and intelligence test scores partialled out. This result is a particularly stringent verification of the hypothesis. The effects of the content of metaphors and of its interaction with age or *M* capacity have been studied by means of the combinations of two tenors and three vehicles. Elaborating the vehicle by means of adjectives has also been studied. The results replicate those obtained with the whole cited set of six metaphors; no interaction of content with age or *M* capacity is found; and the presence of one or more adjectives has no effect. It appears that the vehicle constitutes a single concept, independent of its linguistic extension and from the richness of detail provided by adjectives.

Johnson (1989) studies the comprehension of metaphors presented in Spanish and in English to bilingual children from 7 to 12 years of age, whose mother tongue is Spanish, and who are progressing normally in an English-language Canadian school. This research employs many tests, for the most part verbal, for the purpose of distinguishing the tasks that depend on specific abilities in a particular language from those that, beyond the verbal content, involve more general cognitive resources.

The results show that the metaphor comprehension tasks in English and in Spanish are highly correlated; and, moreover, the correlation between the Figural Intersection Test and metaphor composition in each language is significant and remains so even when a compound index of ability in that specific language is partialled out. This data provides further support for the conclusion of the previous research, namely, for the role of the *M* operator in the interpretation of metaphor.

In conclusion, the TCO seems capable of generating a valid analysis of at least some aspects of language such as metaphor and subordinate clauses (Johnson et al., 1989).[24]

PLANNING AND PRODUCTION OF CHILDREN'S DRAWINGS

Drawing is another form of symbolic representation that Piaget did not investigate extensively. He was interested in drawings mainly as converging evidence for his theory of geometrical knowledge, and accepted Luquet's classical theory of stages in drawing competence, characterized by different levels of realism. Research on drawing takes off again within a Human Information Processing framework (e.g., Freeman, 1980; Willatts, 1987). In this context, Morra (1995) proposes a neo-Piagetian account of development of children's drawing.

Children's drawings are usually schematic; early graphic schemes are formed in the context of scribbling, and their potential meaning is sometimes discovered accidentally or figured out on the spot. Within a few years (roughly between the ages of 3 and 5), however, children acquire a repertoire of graphic schemes that have a meaning for them, or can be used as components of more complex, meaningful drawings. Morra (1995) suggests that a graphic scheme is a hierarchically organized figurative scheme that represents the visual aspect of a previous satisfactory solution that the child has found to a pictorial problem; for instance, a child's graphic

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[24] Also tasks with a nonverbal symbolic content have been studied from the point of view of the TCO: for example, Bell and Kee (1984), Bereiter and Scardamalia (1979), Case (1972, 1974b), Pascual-Leone and Smith (1969).

scheme for a house is derived from the visual aspect of some satisfactory outcome of that child's attempts to draw houses (see also van Sommers, 1984). Also operative schemes are involved in drawing, such as motor schemes, procedures (e.g., for modifying a habitual graphic scheme), drawing systems (e.g., the practical rules of oblique projection, for an older child who masters it, constitute an *LM* structure of operative schemes). Most important in drawing are the operative schemes for spatial placement of items on the page; for example, a young child may draw a circle for the mouth carefully under the circles that represent the eyes; a 4-year-old may acquire a rule to draw figures aligned with the bottom of the page; an older child may arrange the various elements of a scene in selected parts of a sheet.

Metasubjective operators (especially learning and field operators) also have an important role that cannot be reviewed in detail here. Drawing often involves planning and problem-solving, and in such situations the role of the *M* operator comes to the fore. To exemplify drawing research based on the TCO, we report here some studies of partial occlusion (Morra, 2002; Morra, Angi, & Tomat, 1996).

Drawing a Partial Occlusion: Task Analysis

How can a child draw an object that is partly visible, and partly hidden behind something else? Preschoolers tend to draw a partly occluded object as if it were fully visible; this strategy is overcome by a majority of children at an age that varies, across experimental conditions, between 5 and 8 years (see Cox, 1991). A major finding from previous research is the similarity effect; children show a stronger tendency to draw an integral shape for the partly occluded object when the occluding and occluded objects have similar shapes (Cox, 1991).

Morra et al. (1996) suggest that this task involves two misleading factors. One is learning; a child who has a graphic scheme for the object that is partly occluded tends to apply that graphic scheme. The other is a field factor, only involved when the occluding and occluded object are similar; in this case, they are perceptually encoded according to the Gestalt law of grouping, which, in turn, enhances the child's tendency to draw a group of similar forms. Therefore, children may draw clearly separate figures for the two objects, or at best, to convey the idea of the objects' spatial proximity, draw two contiguous but integral figures.

There are two strategies that can yield graphic representation of a partial occlusion. One strategy involves the plan to draw the occluded object's scheme without those lines or components that would usually represent the currently hidden part. This "hidden line elimination" strategy requires activation of three schemes: (a) a figurative graphic scheme for the occluded object, (b) a figurative representation of its hidden part, and (c) an operative scheme that "mentally deletes" from the graphic scheme (a) those components that correspond to the part (b). Therefore, the *M* demand of this strategy is $e + 3$. Moreover, due to the previously mentioned error factors, its use should be correlated with field independence, especially for the case in which the two objects are similar.

The other strategy that can lead to the successful drawing of a partial occlusion requires activation of only two schemes: (a) an operative scheme for placing a graphic scheme on the page in an appropriate position, that is, connected to the drawing of the occluding object; and (b) a figurative graphic scheme for the visible part of the occluded object. The *M* demand in this case would be only $e + 2$; however, this strategy is made difficult not just by the same error factors that hinder the other one, but also by the possibility that the graphic scheme (b) is not easily available, and a child might even need to create it on the occasion.

Therefore, certain predictions follow: first, that the *M* capacity required for partial occlusion drawing is $e + 2$, which is the minimum demand of a successful strategy, and that an increase in partial occlusions occurs when an *M* capacity of $e + 3$ makes both strategies accessible; second, that partial occlusion drawing is also correlated with field independence; and third, that the demands for *M* capacity and field independence are higher in case of similar objects, because in this case, the *F* operator also turns into a misleading factor. One further prediction regards a particular error pattern (called "transparency" because the two objects are drawn partly superimposed, as if the occluding object were transparent). This outcome is assumed to be a consequence of faulty implementation of the hidden line elimination strategy by children who don't yet have the required *M* capacity. Consider the case of a child with a capacity of $e + 2$, who is able to activate only the first two schemes involved in that strategy, but not the third one; the likely outcome would be a "transparency" drawing. Thus, it is predicted that this particular sort of drawing is only produced by children with a capacity of $e + 2$.

Experimental and Correlational Research

Morra et al. (1996) manipulate in an experiment the similarity of the model objects (e.g., a ball behind another ball, versus a pyramid behind a cube) and the visibility of the model while drawing (i.e., for half of the participants the model objects were screened before the child started to draw). The similarity effect proves equally strong with a screened model as with a visible model, which implies that this effect is due to initial perceptual encoding—

rather than, for instance, to observing the model during the drawing process. A second experiment suggests that the similarity effect is actually associated with the Gestalt phenomenon of perceptual grouping.

Further experiments (Morra, 2002; Morra et al., 1996) confirm that, as predicted, partial occlusions are not drawn by children with an M capacity of $e + 1$, that children with $M = e + 3$ draw more partial occlusions than those with $M = e + 2$, and that partial occlusion drawing is correlated with field independence. Morra et al., with a sample of first-graders, find that partial occlusion drawing is related to M capacity and field independence only for model pairs of similar objects; however, with a sample of children in a broader age range (5 to 8), Morra (2002) finds that the drawing of partial occlusions is related to M capacity and field independence with any pair of model objects. In both studies "transparency" drawings are associated with an M capacity of $e + 2$. In contrast, for children with an M capacity of $e + 1$, the most common outcome by far is a drawing of integral and clearly separate shapes of the two objects (Morra, 2002); this simple solution requires mental activation of only one scheme, namely, the one that represents the identity of the partly hidden object.

Pascual-Leone (1989) makes a distinction between the field-dependence tests that are particularly sensitive to figural field factors (e.g., the Embedded Figures test, in which the misleading field derives from perceptual cohesiveness of a meaningful figure, which hinders detection of a smaller figure embedded in it) versus those that are more sensitive to stimulus–response compatibility (e.g. the Rod and Frame test, in which one is biased to align the rod according to the frame's inclination). Based on this distinction, Morra (2002) also studies which tests better predict performance in the drawing task and determines that the single best predictor is the Children's Embedded Figures Test—a test that is sensitive to field factors in perceptual encoding.

A number of other studies examine drawing from the point of view of the TCO. Morra et al. (1988) investigate how children plan in advance the drawing of a complex scene. Morra, Caloni and D'Amico (1994) study children's ability to modify the graphic scheme of a human figure, a tree, or a ship in order to convey an intended emotional meaning. Morra (2005) explores other modifications in the human figure, such as those that represent a particular movement. On the whole, this work accounts well for the drawing tasks under consideration, thus supporting the theoretical view of drawing development suggested by Morra (1995). Other studies have considered a task that involves representation of complex spatial relations, but not in the domain of drawing (Morra, 2001; Morra, Pascual-Leone, Johnson, & Baillargeon, 1991). These studies add further evidence of the TCO's ability to generate useful analyses of spatial tasks.

COGNITIVE DEVELOPMENT AND MOTOR ABILITY

Execution of complex movements may require mental programming, at least until they are sufficiently well practiced as to become automatized. Motor programming is an area of research quite distinct from sensorimotor intelligence and practical intelligence as studied by Piaget. Many argue that the limits of working memory influence the ability to program movements: Smyth and Pendleton (1990) studied the representation of movements in working memory, and Allard and Burnett (1985) studied the formation of complex cognitive units (chunking) that represent sports actions. Developmental research in this area is not extensive; Todor (1975, 1979) opened the way to exploration of this territory.

The motor task that Todor studied is not very complex; it is made up of two component movements, one circular and the other straight. The form of the combined movements resembles an upside down Greek letter *rho*, and thus the name "rho task." The rho task requires not only rapidity, but also coordination of movements. The apparatus itself looks like a rectangular box with a handle close to the person operating it that can be moved circularly to a point where it meets a bumper. On the opposite side of the box there is a target. The task consists of making the circular movement so that the handle hits the bumper, then letting go of the handle and hitting the target with one's hand, all as rapidly as possible (see Fig. 2.2).

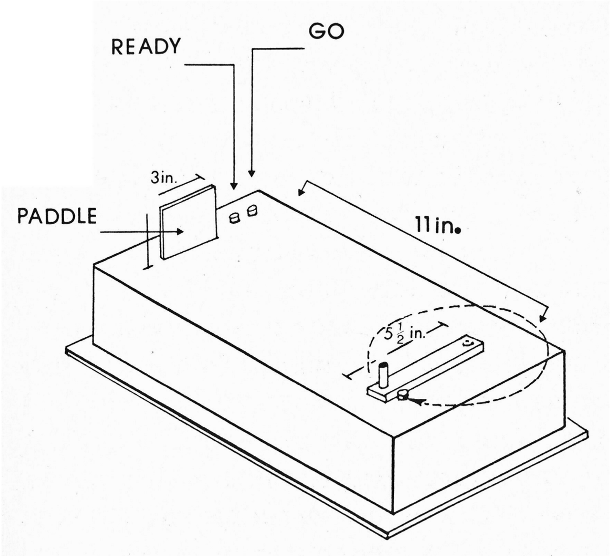

FIG. 2.2. Rho task apparatus. *Source:* Pascual-Leone (1987).

A set of sensors and timers breaks the movement into four phases: the *reaction time* from the "go!" signal to the beginning of the movement; the *rotation time* corresponding to 330 degrees of circular motion; the *pause time* in which the child opens his or her hand, releases the handle to continue of its own inertia, and prepares the movement toward the target; and the *linear time* involved in the straight motion toward the target.

Rho Task Analysis

The analysis of the rho task has been perfected in a series of studies (Pascual-Leone, 1987; Todor, 1975, 1977, 1979). The reaction time and the rotation time are of little psychological interest because they involve only the initiation and execution of a movement and do not require coordination of additional information or motor schemes. However, in the subsequent pause phase and linear phase, someone lacking the ability to form coordinations of the movements would have to first complete the rotation, then decide to open his or her hand and finally to direct the hand toward the target. The more able one is with respect to mentally integrating these components of the complex movement, the more time that can be saved in these phases.

A minimal integration of the components requires an *M* capacity of $e + 3$ given that, although carrying out the circular movement, one must activate[25] simultaneously three operative motor schemes that represent: (1) the arm's movement toward the target, (2) the direction of one's gaze toward the target, and (3) the opening of the hand to let go of the handle. Children with an *M* capacity of $e + 2$ would be able to hold in mind either only the first two schemes and lose time in the pause, or only (1) and (3) and lose time in the linear phase in order to localize the target. Certainly they would not be able to integrate all the necessary schemes into a single program.

The integration of the motor program will be better with an *M* capacity of $e + 4$ because at this level it is possible to include, in addition to the operative schemes already mentioned, a figurative scheme representing either the point in the circular movement at which it would be appropriate to open one's hand or the point for directing one's aim toward the target. By employing such a scheme the pacing of the successive actions can be improved. Further progress is possible with an *M* capacity of $e + 5$. At this level, one can attend to each of the two distinct points in the circular movement, one for opening the hand and one for aiming toward the target, thus

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[25] Although the schemes are simple motor ones, it is reasonable to assume that their activation involves the *M* operator. The circular movement that is being performed and the instruction to do it rapidly induce in their own right a concentration of attention on the movement being executed in that moment. Therefore effortful mental attention is necessary for advance planning of the subsequent movements.

permitting optimal temporal coordination of the actions. Development of *M* capacity to the higher levels of $e + 6$ or $e + 7$ would have no influence on motor coordination in the rho task.

Research on the Rho Task

Todor (1975) compares three groups of children aged 6, 11, and 18. Performance of the 18-year-olds is the fastest, and they require only a few trials to reach the optimal level of performance, after which practice has minimal effect. In the early trials the speed of the 11-year-olds is not as great, but by the final trials their performance is as rapid as that of the 18-year-olds. Although initially low, the correlation between the times for the various components of the movement in the final block of trials is positive, as is also true for the 18-year-olds. With the experience of just a few dozen trials, the 11-year-olds achieve a speed and a degree of integration among the movements similar to that of the 18-year-olds.

The slowest group on the task is the 6-year-olds; but the most notable result in this group is that even though their times improve over the course of the experiment, the correlation between the components of their movements does not improve with practice; in fact, it declines almost to zero. It appears that 30 practice trials are sufficient for these children to accelerate each of the components of the rho movement but not to integrate them into a single program. The results of this research motivated the task analysis described in the section entitled "Drawing a Partial Occlusion: Task Analysis," and subsequent research was carried out to test it.

Todor (1977, 1979) compares eight groups of children ranging from 5 to 12 years of age and chosen by means of the CSVI so that their *M* capacity is normal for their age. Each child completes 25 practice trials on the rho task followed by five trials for which the times are analyzed statistically.

The results support the hypothesis that with each increment of one in *M* capacity there should be a decrease in the pause times and in the linear phase. It is in alternate years that these decreases are observed. Also confirmed is the hypothesis that a particularly large difference should be found with respect to both pause times and linear times between children with an *M* capacity of $e + 2$ and those with $e + 3$ as a result of the inability of the first group to integrate the various actions into a single motor program.[26]

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[26] The increase in *M* capacity from $e + 2$ to $e + 3$ leads to a decrease of 160 milliseconds in the performance time of interest while each successive increase in *M* capacity permits a savings of another 80 milliseconds. One might object that in the year in which the *M* capacity increases from $e + 2$ to $e + 3$, a child's motor speed also increases and that the latter could be the true cause of the obtained result. In order to counter this objection Todor (1979) reports an analysis of covariance in which variability in rotation time is statistically controlled. The differences between the $e + 2$ and the $e + 3$ groups in statistically corrected pause time and linear time remain significant.

As the task analysis predicts, rotation time does improve with age but not as a function of *M* capacity. These results, therefore, demonstrate that the developmental improvement in pause time and linear time, indicative of the degree of motor integration, has a different cause from the improvement in rotation time.

Pascual-Leone (1987) reports another study with 7- to 12-year-olds in which he considers the role of *M* capacity, practice and hemispheric specialization. Each child completes two series of trials on the rho task, first with the right hand and then with the left. After 2 weeks the task is repeated with the left and then with the right. Two hypotheses guide the research. First, some authors suggest that the development of *M* capacity derives primarily from automatization of cognitive processes. If this were so, then Todor's results would be replicated in the first series of trials but not in the fourth as practice would have automatized the components of the motor program. If, however, *M* capacity develops as a function of maturation, Todor's results should be replicated in both the first and fourth series.

Second, Pascual-Leone (1987) wishes to examine whether the executive schemes that control the use of *M* capacity are found in both hemispheres or localized in the dominant one. If the former is the case Todor's results should be replicated with both hands, but in the latter case these results would be found only when (right-handed) children complete the task with the right hand.

The results show a clear relation of pause time and linear time with *M* capacity in the first and fourth series of trials (completed with the right hand). In the second and third series, however, the improvement with age is gradual from 8 years and up. The effect of *M* capacity in the fourth series contrasts with the hypothesis that automatization of processes is the basis of *M* capacity development. The different outcome for the series involving the left hand suggests that the executive schemes regulating *M-capacity* use are lateralized in the dominant hemisphere.

An improvement with practice is found among the youngest children (7–8 years) and may be explained by learning processes (*LC* operator): the children might gradually learn to use proprioceptive feedback for motor coordination in the task. For the older children, who quickly acquire an optimal integration thanks to an *M* capacity of $e + 5$, the additional practice yields little or no benefit.

The research described in this section points at interesting possibilities for the study of motor programming (see also Gerson & Thomas, 1977, 1978). One may ask whether a neo-Piagetian approach is also suitable for more complex motor tasks, important to the children (or adults) who learn them, such as complex sports or dance movements. According to Russell (1990) it is difficult to define cognitively the "problems" in sports, or to identify appropriate units of analysis. Thus, research is often limited to rather abstract laboratory tasks. There are ecologically valid studies on the acquisition of ability in basketball (French & Thomas, 1987) and tennis (McPherson & Thomas, 1989; Williams, Ward, Knowles & Smeeton, 2002) and on memory for movement sequences in modern dance (Starkes, Caicco, Boutilier, & Sevesk, 1990), but these consider only a single cognitive variable, namely the degree of knowledge of the studied activity on the part of the participants. Tallir, Musch, Valcke, and Lenoir (2005), in a study with 10-year-olds, showed that field-independent children were more able at decision making in basketball. Corbett and Pulos (1999) presented a preliminary study, framed within the TCO, of skills like hopping and jumping a rope. There are ample possibilities in this field, and the methods described here could be extended to research on the acquisition of other motor abilities.

RESEARCH ON INHIBITORY PROCESSES

The concept of inhibitory processes in human cognition was not yet popular at the beginning of the Eighties, when so-called "oil-pump" or flowchart models were still the most credited accounts of information processing, except perhaps in language comprehension and memory for narratives. In particular, bottom-up or data-driven models dominated the field of backward pattern masking (see Felsten & Wasserman, 1980, for a review). Backward pattern-masking is a paradigm in visual perception, that consists in brief presentation of a stimulus (e.g., a letter), which after a short interval is replaced by a "mask" (e.g., a random arrangement of letter fragments) that impairs stimulus recognition. Pascual-Leone, Johnson, Goodman, Hameluck, and Theodor (1981) proposed a series of masking experiments, with children aged from 6 to 12 and young adults, as a test of the *I* operator, followed by further experiments with adults of different ages (Pascual-Leone, Johnson, Hameluck, Skakich, & Jedrzkiewicz, 1987).

The basic idea of Pascual-Leone et al. (1981, 1987) is that, on presentation of the mask, a conflict arises between the task executive (a plan to follow the experimenter's instructions and detect the letters) and the orienting reflex (an innate operative scheme that directs attention to any new stimulus, such as the mask). Therefore, stimulus recognition involves suppression of the mask representation, in order to extract relevant stimulus features from the stimulus–mask compound. The better a person is able to ignore the mask—either because of experimental manipulation or individual differences—the more effectively the stimuli will be recognized.

Pascual-Leone et al. (1981, 1987) manipulate an apparently minor aspect of the materials, that is, the fixation stimulus that is presented at the beginning of every trial to direct the participant's attention where the target stimulus will appear. Different fixation stimuli are used; the two main ones are either a single point at the center of the display, or four points arranged in a square pattern demarcating the area where a letter appears. The basic hypothesis is that the four-dot fixation stimulus cues the *I* operator to the area where one must inhibit processing of the irrelevant features displayed in the mask. In agreement with this prediction, all of the experiments showed better performance with the four-dot fixation stimulus. One could object that it is not an inhibitory process that causes this result, but rather automatic activation (i.e., priming) of a certain area in visual space. To test this possibility, Pascual-Leone and colleagues use a five-dot fixation stimulus, that is, the four-dot square configuration plus the single dot in the center. The priming interpretation predicts that the five-dot pattern would yield at least as good performance as would the four-dot pattern, because it would prime the same area with an even greater quantity of materials. According to the *I* operator hypothesis, however, the four-dot fixation stimulus should yield better performance than the five-dot one, because the latter could lead participants to attend either to the square pattern or to the central point. The results support the inhibitory account, because performance with the five-dot fixation stimulus turns out to be intermediate between those with the single dot and those with the four-dot pattern.

The results suggest that (notwithstanding different overall performance at various ages) the advantage for the four-dot pattern over the single dot is roughly constant from 6-year-olds to young adults. (This, incidentally, is another clue that the four-dot advantage is not related to the *M* operator, which develops considerably during this age range.) One experiment also tests Pascual-Leone's (1983) claim that the *I* operator declines in elderly subjects, by comparing different age groups from 20 to 70 years. The results show a decrease with age of the four-dot pattern advantage, and the difference is not significant for the oldest age group. Two experiments, respectively with 11- to 12-year-olds and young adults, also test the effect of individual differences in cognitive style. The results show that field-independent participants perform better and, in particular, are better able to take advantage of the four-dot pattern than field-dependent participants. This result rules out the possibility that the advantage of the four-dot stimulus is due to the *F* operator (otherwise the outcome would have been quite the opposite); it cannot be accounted for by traditional, bottom-up models of visual masking, and provides further support to Pascual-Leone's model, which predicts that in situations of cognitive conflict field-independent people are more efficient in using the *I* operator or the executive schemes that control it.

It is unfortunate that those experiments were not published in major journals; perhaps they were too much too much ahead of their time. Although they do not clarify every property of the *I* operator, they provided evidence in favor of such a construct, when it was not obvious at all. Recent research has undertaken the study of the *I* operator again, comparing different experimental paradigms in which it may be involved.

Comparing Inhibitory Processes Across Tasks

Johnson et al. (2003) consider two different speeded tasks in which the *I* operator might be involved: a Stroop task and a spatial location task, both designed according to the logic of negative priming. These tasks are given (along with other measures[27]) to samples of children in the age range from 6 to 11.

The Stroop task has three conditions: (a) A control condition, in which rows of X's in various colors are presented for color naming; (b) An interference condition, in which color names written in a different color are presented for color naming, and consecutive items have no feature in common; for example, the word "blue" written in orange is followed by the word "green" written in yellow, and the child must respond "orange" to the first item and "yellow" to the second; and (c) A negative priming condition, similar to (b), except that each item is printed in the same color that was the meaning of the word in the previous item; for example, the word "blue" written in orange is followed by the word "green" written in blue, then by the word "black" written in green, and so on. It is known from previous research (e.g., Tipper et al., 1989) that responses in condition (b) are slower than in condition (a) because of the interference of word reading on color naming, and that condition (c) is even slower, because responses are delayed not only by interference, but also by negative priming. When response times (RTs) show a relatively *small* difference between conditions (b) and (a) this is taken as an indicator of efficient inhibition, that is, resistance to interference. When RTs show a relatively *large* difference between conditions (c) and (b) this, too, is taken as an indicator of efficient inhibition, because a large negative priming effect suggests that the irrelevant features of the previous item had been strongly inhibited.

The spatial location task uses a display with four squares, located up, down, left, and right on a screen. In each item, a colored patch appears in the center of the screen and two X's (one in the same color as the central patch and one in a different color) appear in two of the four squares. The child's task is to rapidly move a joystick to the location of the X cued by the color of the central patch. Items appear in pairs, that is, a prime and a probe item. There are actually four conditions defined by the prime–probe

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[27] These are: two tests of *M* capacity (the CSVI and the FIT), some measures of processing speed, and a test (called Trail Making) that involves planning an unfamiliar sequence. An important outcome, that here cannot be reported in detail, is that three constructs are clearly distinguished. *M* capacity is not accounted for by either speed or inhibition. Also inhibition is not accounted for by speed.

relationship, but describing two is sufficient here: (a) a control condition, in which the two squares used in the probe are those that were not used in the prime; (b) a negative priming condition, in which the distracter X is presented in a square that was not used in the prime, but the target X appears in the same square where the distracter appeared in the prime item. Note that in this task there is no condition defined as interference. In the Stroop task, each stimulus has two features that tend to elicit different responses, so that a person must select the relevant feature and suppress the salient but irrelevant one. In this task each stimulus also has two features (a color and a location), but these two features of the same stimulus do not elicit different responses; rather, the color cues target selection, and then one can respond to the target's location. Previous research (e.g., Milliken, Tipper, & Weaver, 1994) shows that, even though this task involves no interference, it does yield a negative priming effect, that is, responses are slower when the probe target appears in the same place as the prime distracter. Moreover, negative priming in response to location seems to be manifest at an earlier age (e.g., Simone & McCormick, 1999) than in the context of a Stroop task (e.g., Tipper, Bourque, Anderson, & Brehaut, 1989). The study by Johnson et al. (2003) attempts to solve the puzzle of why negative priming emerges at different ages in these tasks.

The results for the two tasks considered separately are consistent with those of previous research. In the spatial location task a negative priming effect is found (of about 50 msec), that is highly significant and independent of age. In the Stroop task, a large interference effect is found; it is significant in both younger (6–8) and older (9–11) children, but is larger in the younger group. At the same time the negative priming effect is significant in the older group (having a magnitude of about 80 msec per item), but is negligible and nonsignificant in the younger group.

The correlations among these effects shed some light on different forms of negative priming. There is a negative correlation between interference and negative priming effects in the Stroop task. This result is in agreement with the view that, in that paradigm, those children who can better inhibit the irrelevant features in a Stroop stimulus and, thus, show a smaller interference in one condition, also show a larger negative priming in another condition where inhibition of irrelevant features of the previous item turns into residual inhibition of relevant features of the subsequent item. However, negative priming in the spatial location task is clearly uncorrelated with both negative priming in the Stroop task, and with interference in it. That is, the Stroop and the spatial location paradigms tap two different and unrelated forms of negative priming.

Johnson et al. (2003) interpret the results according to Pascual-Leone's (1984) distinction between effortful and automatic interruption. The Stroop task would require effortful inhibition because of its misleading nature (the presence of contradictory features in each stimulus, which requires the subject to filter out the most salient but irrelevant of them). Therefore, considering individual differences, negative priming is associated with reduced interference; and considering age-group differences, it is not possible for children younger than a certain age (that in this paradigm turns out to be 9 years) to apply successful interruption in the task. The spatial location task, instead, can be described as distracting (because two stimuli appear and only one must be responded to) but not misleading (because the two stimuli are easily distinguished and their properties make clear which one must be responded to). Hence, no effortful inhibition is needed. Instead, automatic inhibition is produced (at all ages, and without any specific relation to task difficulty) as a consequence of the choice to respond to the stimulus in a particular location—and ignore the other one.

A further study with adults (Johnson et al., 200) has a similar design. It includes three tasks that are known to produce negative priming, that is, the Stroop task and the spatial location task just described, and a paradigm that involves letter naming under different memory loads (from Engle, Conway, Tuholski, & Shisler, 1995). In this task two superimposed letters are presented, one red and one green, and the participant must name aloud quickly the red letter while ignoring the green one. Items are arranged in pairs, that is, a prime and a probe. In the control condition, both letters in the probe are different from the two in the prime. In the negative priming condition, the distractor (green letter) in the prime becomes the target (red) in the probe. Furthermore, the letter naming task is embedded within a word memory task. A prime–probe sequence can be presented under different memory loads; that is, a variable number of words, ranging from 0 to 4, are presented before the prime, and the participant encodes them for recall after responding to the probe. Engle et al. (1995) suggest that naming the red letter while ignoring the superimposed green one demands effortful selection, and therefore, inhibition is maximally efficient without a memory load, but less efficient with increasing memory load because a person has less resources available. Therefore, Johnson et al. (2005) assume that negative priming under load = 0 is an index of effortful inhibition, but negative priming under load = 4 is not.

Four negative priming measures (i.e., RTs in the negative prime condition with RTs in an appropriate comparison condition partialled out) in this study are of interest here: (1) in the Stroop task, (2) in the spatial location task, (3) in the letter naming task without memory load, (4) in the letter naming task under load = 4. The results show that (1) and (3) are positively correlated, which is consistent with the view that they both represent the outcome of effortful interruption. Also (2) and (4) are positively correlated, consistent with the view that they both represent the outcome of automatic interruption that follows selection. All other correlations, instead, are negative (although only one of them is significant); Johnson et al. (2005) suggest that, at the very least, automatic and effortful inhibitory processes are unrelated to each other, and that they may possibly even be two negatively related styles—in the sense that people who are most efficient in effortful, strategic interruption might be less prone to automatic interruption.

These studies seem to mark a progress in the study of the properties of the *I* operator, and its individual and developmental differences. Furthermore, they are carried out in closer connection with "mainstream" information-processing research (that was not the case of early neo-Piagetian studies of inhibitory processes as mainstream cognitive psychology at that time had not yet begun to study inhibition directly), with more than a chance that such reciprocal influence can benefit both sides.

CONCLUSION

The TCO was the first theory to define itself neo-Piagetian; it inaugurated the unification of Piagetian, information-processing, and individual-differences approaches in a single theory of cognitive development. It includes different learning mechanisms for the formation of new schemes; it regards maturation of an attentional resource (the *M* operator) as a precondition for developmental transitions, and it considers the interplay of various "metasubjective operators" as a dynamic factor of conflict resolution, which sometimes develops into a new equilibrium. The merits of the TCO, however, are not just historical. As we have shown throughout the chapter, it has evolved considerably from the first formulations (Pascual-Leone, 1969, 1970; Pascual-Leone & Smith, 1969).

Some of the main ideas of the TCO were long disregarded by mainstream researchers. According to Pascual-Leone's (1987) own recollection, "In 1963 I proposed to Piaget the concept of a mental capacity, or mental-attention mechanism, capable of boosting a limited number of schemes . . . Piaget understood very well this idea . . . but did not like it" (pp. 532–533). For decades, this idea was given little consideration by orthodox Piagetians, empiricist learning-oriented researchers, or proponents of flowchart models. At best, it was misunderstood as a concept akin to short-term memory. Today, however, many researchers accept the view of attentional resources that limit working memory capacity and constrain cognitive development. Similarly, the idea of an inhibitory mechanism—not just an attentional filter that excludes aspects of the perceptual input from processing, but a cognitive resource also involved in thinking and problem solving—was foreign to the mainstream models of cognitive psychology. But the idea of inhibitory attentional resources is now common. The idea of multiple metasubjective operators that could interact and also conflict with one another originally sounded almost science-fiction, but from the 1990s, a similar approach has been proposed, for instance, within dynamic systems models and connectionist models of executive control.

The TCO is still evolving; research on what is termed *M* or *I* operator in the TCO now feeds into the current lines of mainstream research on the basic mechanisms of cognition, and the TCO's dialectical models of development in various cognitive domains are accepted with much less skepticism. Aspects of the TCO still need to be developed further; for instance, formalization of the *I* operator mechanisms is very much a work in progress. Some other metasubjective operators and the interactions among them also need further elaboration, either in general conceptual terms or in the specific way they affect performance on particular tasks. And perhaps the development of computational models based on the TCO could improve the conceptual precision of its constructs.

Current research on such topics as giftedness (Johnson et al., 2003; Johnson, Pascual-Leone, Im-Bolter, & Verrilli, 2004; Pascual-Leone, Johnson, Verrilli, & Calvo, 2005), specific language impairment (Im-Bolter, Johnson, & Pascual-Leone, 2006), vocabulary learning (Morra & Camba, 2005), reading comprehension in the life span (Borella & de Ribaupierre, 2006), and arithmetical ability (Agostino, Im-Bolter, Johnson, & Pascual-Leone, 2005) shows that this theoretical approach is productive and capable of exploring new areas. This chapter has presented the overall structure of the TCO and some lines of research carried out in this framework. In the following chapters (particularly chaps. 6, 8, and 9), we mention other contributions of the TCO and highlight its similarities and differences with other neo-Piagetian theories.